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Exploratory Studies of Element Interactions and Composition Dependencies in Radiation Sensitivity Development

ORIGINAL

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Materials Engineering Associates, Inc.

Prepared for
U.S. Nuclear Regulatory
Commission

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Exploratory Studies of Element Interactions and Composition Dependencies in Radiation Sensitivity Development

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ABSTRACT

This investigation with laboratory melts of pressure vessel steels (A 533-B or A 302-B base) probes suspect interactions between copper impurities and manganese, molybdenum, chromium and nickel alloying as influencing elevated temperature, radiation sensitivity development. The investigation also qualifies the influence of phosphorus content on radiation sensitivity as a function of copper content and explores suspect contributions of tin and arsenic. Radiation resistance is judged on the basis of Charpy-V (C_v) notch ductility before and after 288°C irradiation to $\sim 2.5 \times 10^{19} \text{ n/cm}^2$, $E > 1 \text{ MeV}$. The findings demonstrate clearly that important composition interactions exist in radiation sensitivity development.

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1. INTRODUCTION

This study is one of a continuing series of investigations by Materials Engineering Associates (MEA) for the Nuclear Regulatory Commission (NRC) to isolate and develop a full understanding of composition influences on the radiation embrittlement sensitivity of reactor vessel steels. The investigation builds on earlier studies with split laboratory melts which revealed that, individually, copper and phosphorus have a detrimental effect on the elevated temperature ($\sim 288^\circ\text{C}$) radiation resistance of typical vessel steels (Ref. 1). The original isolation of the phosphorus effect is illustrated in Fig. 1. Investigations have also revealed that synergisms can and do exist between elements. Specifically, recent studies verified a long suspect synergism between nickel alloying and copper impurities in radiation sensitivity development (Ref. 2). The present set of investigations was undertaken to qualify other suspect element interactions and composition dependencies. The objective was to provide key information for making further refinements to NRC Regulatory Guide 1.99 which is used for estimating radiation embrittlement vs. fluence (Ref. 3). In addition, the results could contribute a better understanding of certain power reactor surveillance data.

This document is the first report of findings from this program.

2. APPROACH

The focus of the composition matrix chosen for study is on binary and tertiary element combinations identified by data bank reviews as having a high probability of correlation with radiation sensitivity. The primary base composition for melting was A 302-B or A 533-B. For the most part, the matrix reflects high or low limits of steel alloying specifications. Alloying limits for A 508-2, a forging grade, were also considered in the selection of element combinations and composition ranges for investigation. Possible interactions of copper with manganese, molybdenum and/or chromium alloying were one major interest. A second was the relative effect of progressively higher phosphorus contents on the radiation resistance of high vs. low copper content steel. Additionally, the matrix was designed to permit exploratory tests of arsenic and tin content contributions to apparent 288°C radiation sensitivity. These elements, like phosphorus, are commonly grouped as contributors to another form of steel embrittlement, temper embrittlement. Finally, the matrix enabled further investigation of the nickel and copper synergism. Relative radiation sensitivity is judged from comparisons of Charpy-V (C_v) notch ductility wrought by a fluence of $\sim 2 \times 10^{19} \text{ n/cm}^2$, $E > 1 \text{ MeV}$, at 288°C .

3. MATERIALS

The materials matrix is shown in Table 1. A series of seven (4-way split) laboratory melts of steel were cast as a means of obtaining statistical combinations of specific impurities and/or alloying

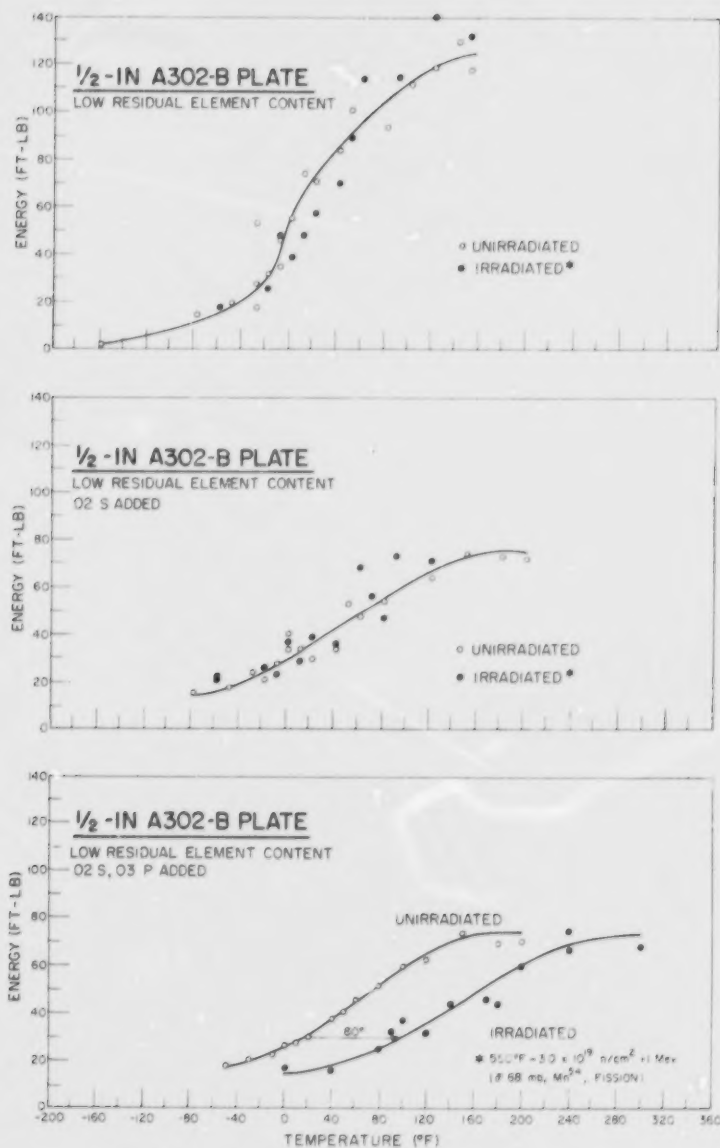


Fig. 1 Notch ductility of A 302-B steel test plates from a laboratory (3-way split) melt before and after 288°C (550°F) irradiation. The Charpy-V notch specimens were irradiated in the same experiment assembly.

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Table 1 Chemical Compositions of Plates from Laboratory (4-Way Split) Melts of Steel
(A 302-B or A 522-B Base Composition)

Melt No.	Plate/ Cast No.	Chemical Composition (Weight-%)												
		C	Mn	P	S	Si	Cu	Ni	Cr	Mo	As	Sn	N	B
1	66A	0.24	1.30	0.018	0.018	0.21	0.16	< 0.002	< 0.003	0.52	-----	< 0.004	0.010	0.0005
	66B						0.16		0.25					
	66C						0.32		0.25					
	66D						0.32		0.52					
2	67A	0.23	1.31	0.003	0.018	0.20	0.002	0.70	< 0.003	0.51	-----	< 0.004	0.009	0.0004
	67B			0.015								< 0.004		
	67C			0.025								< 0.004		
	67D			0.025								0.024		
3	68A	0.23	1.31	0.003	0.017	0.22	0.30	0.70	< 0.003	0.52	-----	0.004	0.010	0.0006
	68B			0.016								0.004		
	68C			0.028								0.004		
	68D			0.028								0.023		
4	69A	0.23	1.23	0.016	0.018	0.24	0.19	0.30	< 0.003	0.53	< 0.010	< 0.004	0.010	0.0005
	69B							0.30			< 0.010	0.021		
	69C							0.70			0.010	0.021		
	69D							0.70			0.033	0.021		
5	70A	0.23	0.88	0.004	0.018	0.22	0.18	0.005	< 0.003	0.37	-----	< 0.004	0.008	0.0005
	70B						0.18			0.66				
	70C						0.33			0.66				
	70D		1.62				0.33			0.66				
6	71A	0.24	0.87	0.003	0.019	0.21	0.18	< 0.002	< 0.003	0.36	-----	< 0.004	0.009	0.0006
	71B		1.63				0.18			0.36				
	71C		1.63				0.32			0.36				
	71D		1.63				0.32			0.67				
7	72A	0.23	1.31	0.020	0.019	0.21	0.33	0.25	< 0.003	0.52	< 0.010	< 0.004	0.009	0.0004
	72B							0.71	< 0.003		< 0.010			
	72C							0.71	0.50		< 0.010			
	72D							0.71	0.50		0.035			

elements (28 combinations, total). The primary base compositions of A 302-B and A 533-B have been used extensively in reactor pressure vessel fabrication, both in the USA and abroad. The specified nitrogen content (0.010% N, *aim*) provided comparability with electric furnace melts. Ingots from the melts were rolled to 15-mm gage plates. These, in turn, were heat treated to microstructures typical of 150-mm and thicker plates at the quarter-thickness location. Heat treatments applied to the plates are included in Table 2. The code numbers assigned to the plates, indicated in this table, are used to identify the individual data sets.

Microstructures of the plates from the melts are illustrated in Figs. 2 through 8. The structures with exception of those for plates 70A and 71A are tempered upper bainite or tempered upper bainite with traces of free ferrite and are typical of those found in heavy gage vessel plates. Because the microstructures are quite similar to one another, the task of making plate-to-plate comparisons for relative radiation sensitivity was greatly simplified. In contrast, plates 70A and 71A contain a significant amount of ferrite in addition to tempered upper bainite as a result of their lean chemistry (% Mn, Mo).

Preirradiation tensile properties and preirradiation notch ductility properties for melts 67 through 72 are given in Tables 2 and 3, respectively. Specimens were oriented in the longitudinal (LT, strong) orientation where the long specimen dimension is parallel to the primary plate working direction. In the case of the tensile specimens, the test materials (blanks) were heat treated (tempered) as a group and separately from the main plates. The similarity noted in properties among the materials also simplified postirradiation analyses.

Appendix A provides full details of material melting and processing to plate. The melting and heat treatment of the materials were carried out by U. S. Steel Corporation, Applied Research Laboratory, under contract.

4. IRRADIATION MATRIX

One experimental objective was the development of full curve C_v properties for the irradiated condition of each material. Requisite specimen numbers, in turn, necessitated a division of the materials among several (four) irradiation assemblies (see Table 4). Typically, a complement of 11 C_v specimens was provided for each material. Preirradiation tests indicated that this specimen number would yield postirradiation C_v properties having a reasonably high confidence level, that is, sufficient for development of plate intercomparisons (the objective) as opposed to the establishment of exact plate properties. As a precaution against material-to-material exposure differences (temperature or fluence), specimens within each irradiation assembly were statistically randomized. Expected variations in ambient exposure conditions were small, however, due to the particular irradiation assembly design and irradiation facility used.

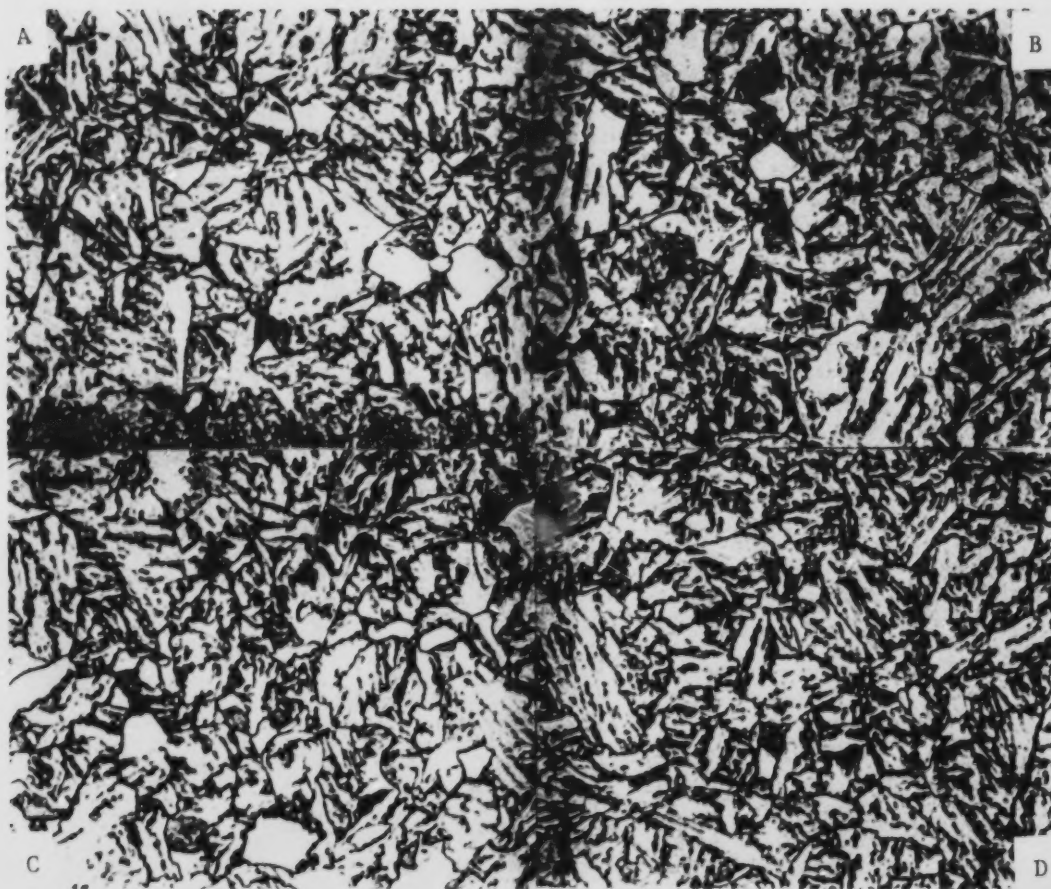
Table 2 Ambient Temperature, Tensile Properties and Heat Treatments (Preirradiation Condition)

Plate Code ^a	Yield Strength ^b 0.2% Offset		Tensile Strength		Elongation in 25.4 mm	Reduction in Area	Heat ^c Treatment
	(MPa)	(ksi)	(MPa)	(ksi)	(%)	(%)	
66A	469	67.97	619	89.82	27.2	66.0	1
66B	482	69.97	640	92.83	----	----	1
66C	492	71.38	644	93.43	----	----	1
66D	514	74.59	666	96.64	24.3	66.4	1
67A	454	65.96	608	88.22	26.0	67.9	1
67B	465	67.37	624	90.43	----	----	1
67C	481	69.77	624	90.43	----	----	1
67D	476	68.97	633	91.83	26.4	67.3	1
68A	460	66.77	621	90.02	25.9	64.6	1
68B	449	65.16	637	92.43	----	----	1
68C	477	69.17	646	93.63	----	----	1
68D	481	69.77	647	93.83	25.3	65.0	1
69A	467	67.77	620	89.82	25.6	67.9	1
69B	461	66.97	614	89.02	----	----	1
69C	474	68.77	633	91.83	----	----	1
69D	466	67.57	626	90.83	26.7	65.5	1
70A	408	59.15	563	81.60	28.3	67.3	2
70B	447	64.76	597	86.62	----	----	1
70C	458	66.37	604	87.62	----	----	1
70D	485	70.38	632	91.63	25.1	65.5	1
71A	408	59.15	563	81.60	30.4	67.3	2
71B	435	63.16	583	84.61	----	----	1
71C	444	64.36	597	86.42	----	----	1
71D	485	70.58	637	92.43	25.4	67.0	1
72A	477	69.17	625	90.63	26.6	66.0	1
72B	474	68.77	640	92.83	----	----	1
72C	538	77.99	690	100.05	----	----	1
72D	527	76.39	688	99.85	23.8	67.3	1

^a Specimen blanks removed from austenitized plate and then tempered

^b Single determinations; gage diameter 6.4 mm, gage length 25.4 mm

^c Heat Treatment: (1) 899°C-1 hr, AC; 649°C-1 hr, WQ; 677°C-5 hr, WQ
(2) 899°C-1 hr, AC; 649°C-1 hr, WQ



550X

Fig. 2 Microstructures of plate codes 66A, 66B, 66C and 66D.



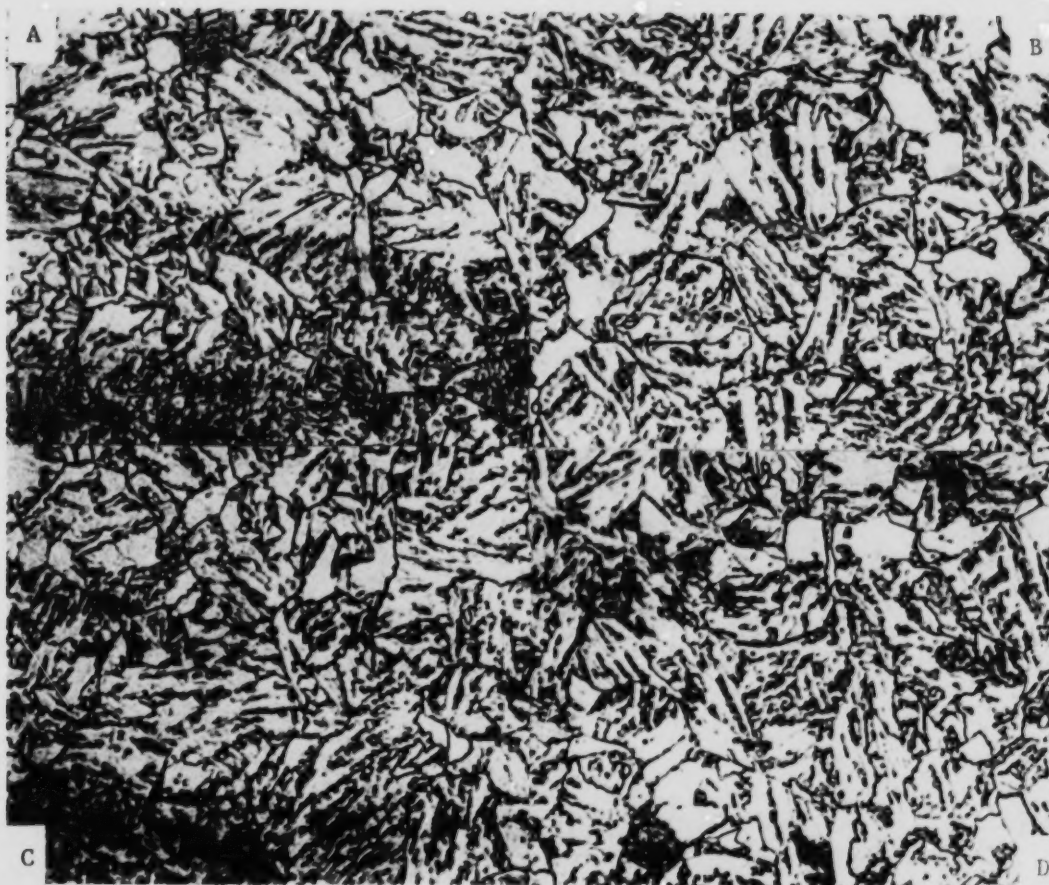
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Fig. 3 Microstructures of plate codes 67A, 67B, 67C and 67D.



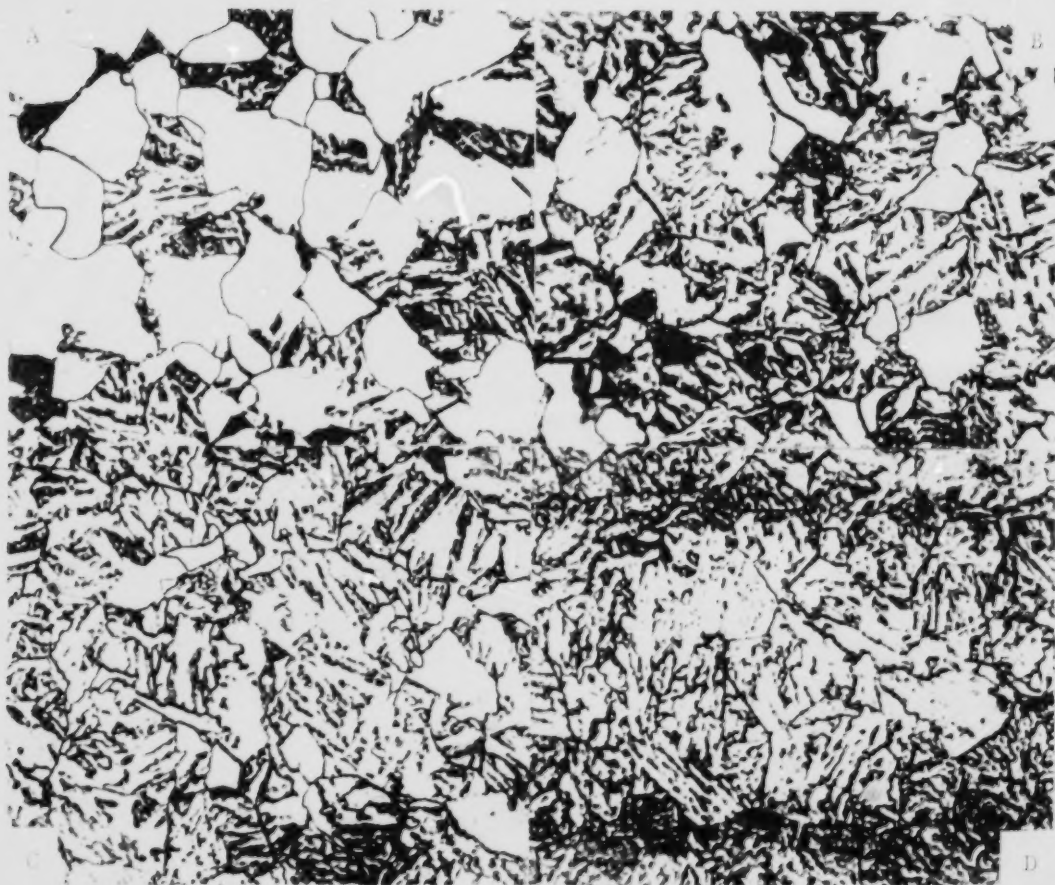
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Fig. 4 Microstructures of plate codes 68A, 68B, 68C and 68D.



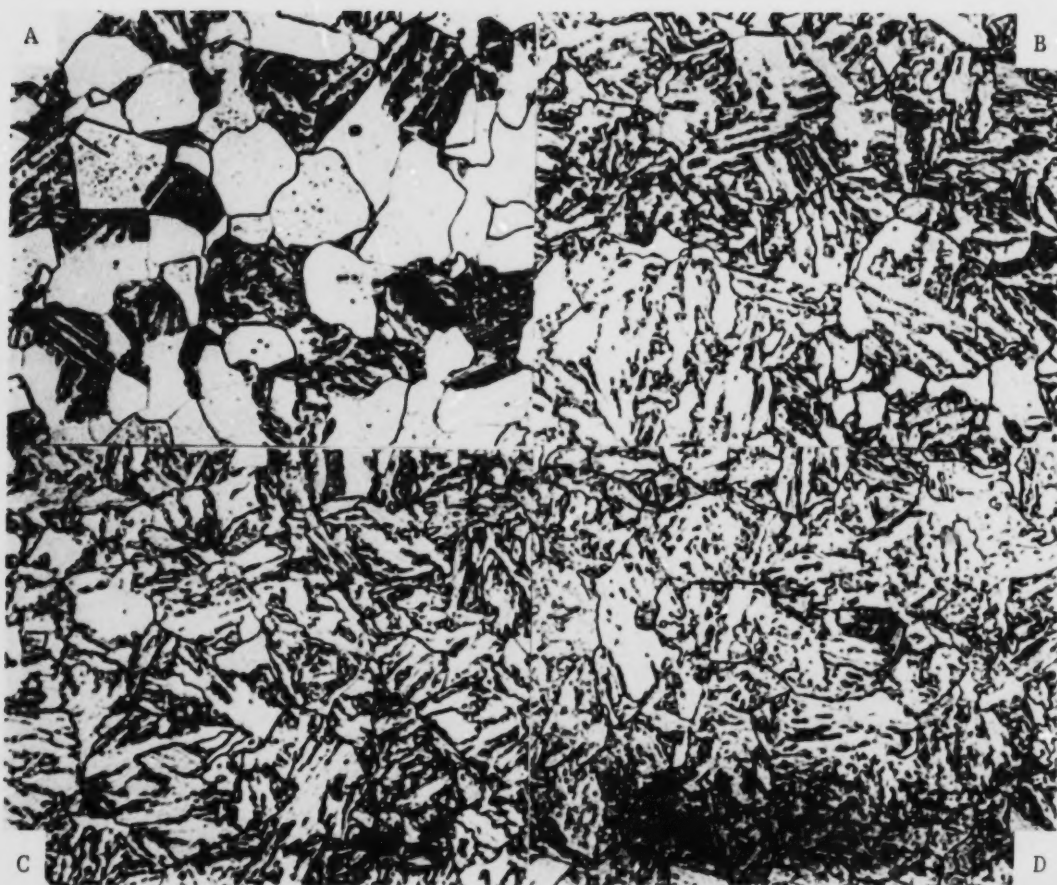
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Fig. 5 Microstructures of plate codes 69A, 69B, 69C and 69D.



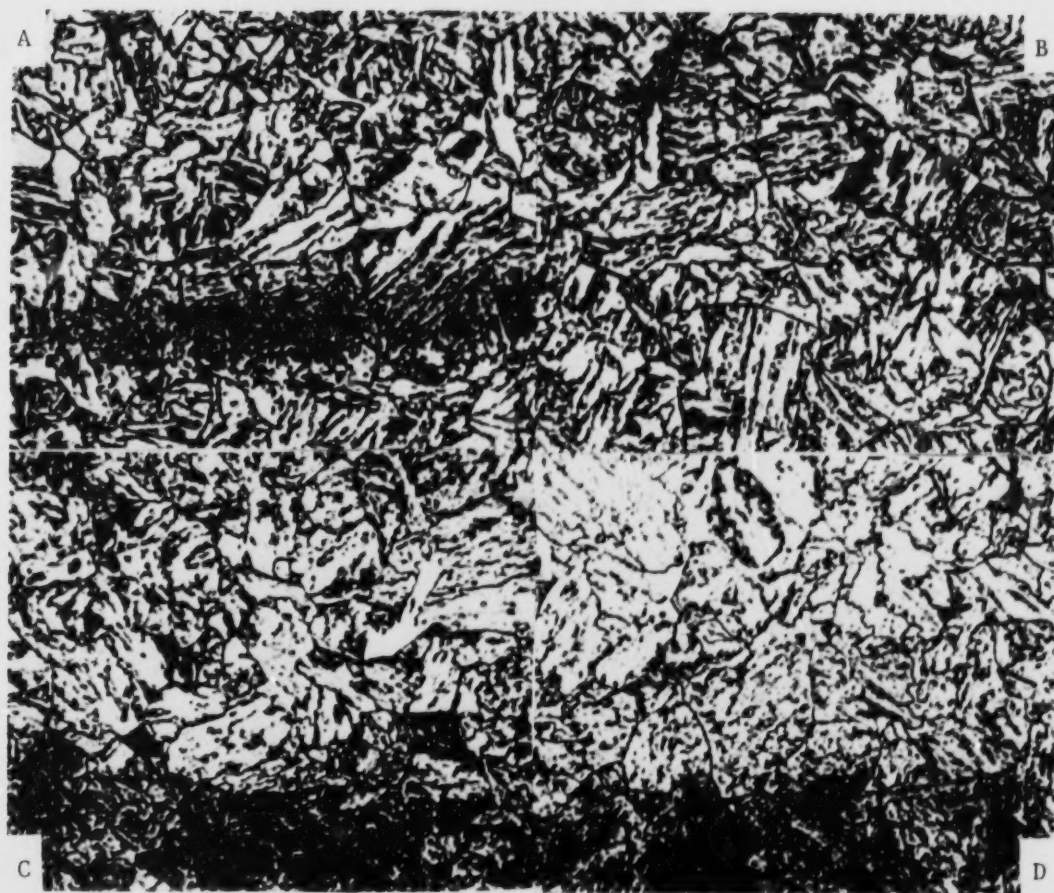
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Fig. 6 Microstructures of plate codes 70A, 70B, 70C and 70D.



550X

Fig. 7 Microstructures of plate codes 71A, 71B, 71C and 71D.



550X

Fig. 8 Microstructures of plate codes 72A, 72B, 72C and 72D.

Table 3 Preirradiation Charpy-V Notch Ductility Properties

Plate Code	Charpy-V Properties											
	41-J Index ^a		USE ^a		41-J Index ^b		USE ^b		A ^b	B ^b	C ^b	T ₀ ^b
	(°C)	(°F)	(J)	(ft-lb)	(°C)	(°F)	(J)	(ft-lb)	(J)	(J)	(Δ°C)	(°C)
67A	-7	20	~ 163	~ 120	-6.2	20.8	170	125	82	88	64	27
67B	-7	20	168	124	-5.8	21.6	171	126	73	98	89	24
67C	-23	-10	152	112	-16.9	1.6	155	114	72	83	67	8
67D	-15	5	152	112	-11.1	12.0	157	116	67	90	86	15
68A	-18	0	151	111	-15.2	4.6	156	115	83	73	62	25
68B	-18	0	145	107	-15.6	3.9	163	120	73	90	81	15
68C	-7	20	144	106	-8.5	16.7	149	110	79	70	51	23
68D	--	25	---	98	-7.3	18.9	149	110	75	74	62	23
69A	-15	5	157	116	-8.1	17.4	159	117	89	70	47	32
69B	-15	5	157	116	-13.9	7.0	158	117	77	81	53	12
69C	-12	10	155	114	-11.0	12.2	157	116	77	80	55	16
69D	-12	10	145	107	-13.3	8.1	147	108	60	87	67	2
70A	-34	-30	148	109	-34.4	-29.9	147	108	49	98	84	-27
70B	-9	15	163	120								
70C	-12	10	152	112	-10.3	13.5	160	118	72	88	48	7
70D	-1	30	149	110	0.1	32.2	156	115	59	97	84	16
71A	-34	-30	126	93	-31.8	-25.2	128	94	46	82	55	-28
71B	-26	-15	176	130	-29.2	-20.6	192	142	40	152	117	-29
71C	-32	-25	156	115	-31.6	-24.9	178	131	61	117	79	-17
71D	13	55	146	108	13.5	56.3	154	114	73	81	62	40
72A	-7	20	~ 144	~ 106	-8.1	17.4	147	108	68	79	66	16
72B	-7	20	~ 144	~ 106	-11.6	11.1	155	114	57	98	84	2
72C	-23	-10	145	107	-21.3	-6.3	143	105	76	67	54	10
72D	-12	10	140	103	-10.4	13.3	136	100	77	59	40	19

^a Eyeball curve fit^b Tanh curve-fit procedure

Table 4 Irradiation Experiment Matrix

Experiment Assembly	Irradiation Facility ^a	Plate Codes	Specimen Type(s)	Hours of Exposure ^b	Average Fluence ^c ($\times 10^{19}$)
VRS-1 (UBR-39)	B-4	67A	Charpy	728.3	2.50
		67B			
		67C			
		67D			
		68A			
		68B			
		68C			
VRS-2 (UBR-40)	B-4	69A	Charpy	742.35	2.38
		69B			
		69C			
		69D			
		72A			
		72B			
		72C			
VRS-3 (UBR-54)	C-2	70A	Charpy	752.22	2.34
		70B		A & C units)	
		70C			
		70D		705.45	
		71A		(B unit)	
		71B			
		71C			
VRS-4 (UBR-56)	B-4	66A	Charpy	749.52	2.31
		66B		(A & C units)	
		66C			
		66D			
		All Codes	Tensile	635.55	(B unit)

^a UBR fuel core lattice position^b Reactor hours at full power (2 MW)^c n/cm^2 , $E > 1 \text{ MeV}$ (calculated spectrum)

Experiment no. 1 (MEA VRS-1) contained C_v specimens from the two melts made to explore the relative level of phosphorus effect in high vs. low copper content steel. These melts also allowed an exploration of tin content effects. Experiment no. 2 (VRS-2) contained C_v specimens of the materials designed to assess further the nickel-copper synergism and to test for tin, arsenic and chromium content effects for the case of a significant phosphorus (and nickel) content. Experiment no. 3 (VRS-3) held the materials for assessing copper in combination with manganese alloying and molybdenum alloying. Finally, experiment no. 4 (VRS-4) contained tensile specimens of all 28 melt combinations plus C_v specimens of the melt forming the copper-chromium series.

This report presents findings from experiments VRS-1, VRS-2 and VRS-3 only. Data from experiment VRS-4 will not be available until late CY 1985 and thus will be covered in a future report.

5. MATERIAL IRRADIATION

The materials were irradiated at a controlled temperature of 288°C (550°F) in a fuel lattice position, B-4, of the 2MW, light-water cooled and moderated test reactor, UBR, located at the Nuclear Science and Technology Facility in Buffalo, New York. Irradiation temperatures were monitored throughout the exposure period with 36 thermocouples attached to the individual C_v specimens. Neutron fluences (n/cm^2 , $E > 1$ MeV) reported here were determined from iron and nickel dosimeter wires distributed over the specimen arrays and located in the specimen V-notches. Fluences are based on a calculated neutron energy spectrum. For the B-4 position, fluence values and the values of displacements per atom (dpa) have the relationship:

$$dpa = 2.486 \times 10^{-15} (\text{neutron fluence, } E > 1 \text{ MeV}) \quad (1)$$

6. RESULTS

6.1 Unirradiated Condition

Individual C_v test results for the unirradiated condition are tabulated in Appendix B. The 41-J temperature was the arbitrary index chosen for determining the C_v brittle/ductile transition before and after irradiation.

The energy vs. temperature data for each plate were curve fit by two methods: the hand-drawn (eyeball) curve-fitting method and a computer curve-fit (tanh) procedure. The index values for each tanh curve fit are included in Table 3. Individual computer-drawn C_v curves are given in Appendix C.

In general, good agreement was observed in the 41-J (30-ft-lb) temperature values derived independently by the two methods. The upper shelf values by the two methods also show good correspondence although

the tanh-fit upper shelf values tend to be slightly higher than those given by the hand drawn curves. Computer curve fitting, while removing any inherent bias of individuals, does not lend itself well to the asymmetry found in some A 302-B and A 533-B data sets. In this report, judgments of relative notch ductility are based primarily on hand-drawn curve fits. Other MEA comparisons of tests of curve-fitting methods have been documented (Ref. 4).

6.2 Irradiated Condition

Table 5 summarizes the findings for the several melts after irradiation. Radiation-induced changes in 41-J temperatures are illustrated in Figs. 9 to 13. Individual C_v test results are listed in Appendix D; companion computer curve fits of the data are compiled in Appendix E.

6.2.1 Melts 67 and 68 (Copper/Phosphorus Series)

Data from these two melts (see Fig. 9) show the (expected) detrimental influence of a high (0.3%) copper content on 288°C radiation resistance (Refs. 1, 5, 6). Of greater significance, the data reveal that the level of phosphorus contribution to radiation sensitivity development is highly dependent on the amount of copper present. That is, the contribution is most pronounced when copper is low. This finding not only provides an explanation for the inconsistencies found in earlier computer treatments of irradiation data banks for the phosphorus effect but reinforces the importance of qualifying suspect paired element and tertiary element combinations for interactions. With respect to the former, existing data banks consist largely of data for high copper, high phosphorus or low copper, low phosphorus content steels. The absence of high-low combinations of the two elements would preclude indications of the phosphorus influence (or its inverse dependence on copper content).

In Fig. 10, results for melt 67 are compared to MEA results for an earlier split laboratory melt. Again, a strong contribution of phosphorus to the radiation sensitivity level of the steel is evident. In this case, the base composition of the melt is A 302-B; the content of 0.15% Cu is judged to be an intermediate level of copper.

Referring to casts C and D of both melts, the increase in tin content (from < 0.004 to 0.024 wt-%) did not change the apparent radiation sensitivity in either case from the standpoint of the transition temperature elevation or the upper shelf decrease by irradiation. The phosphorus content of these melts is 0.02% or 0.028% P. As noted in the next section, an influence of tin content on radiation sensitivity was observed with other plates from the matrix.

6.2.2 Melts 69 and 72 (Nickel/Copper/Tin/ Arsenic Series)

Casts A vs. B of melt 69 (see Fig. 11) do show a contribution of tin to radiation sensitivity. The phosphorus content of these materials (0.017%) is lower than that of melts 67 and 68 above. The detrimental

Table 5 Postirradiation Charpy-V Notch Ductility Properties

Plate Code	Charpy-V Properties													
	41-J Index ^a		USE ^a		Δ 41-J Index ^a		Δ USE ^a		41-J ^b Index	USE ^b	A ^b	B ^b	C ^b	T _O ^b
	(°C)	(°F)	(J)	(ft-lb)	(Δ°C)	(Δ°F)	(ΔJ)	(Δft-lb)	(°C)	(J)	(J)	(J)	(Δ°C)	(°C)
67A	4	40	152	112	11	20	11	8	6.1	159	72	86	58	28
67B	38	100	133	98	44	80	35	26	38.9	134	59	75	69	56
67C	49	120	117	86	72	130	35	26	56.5	121	72	49	40	87
67D	57	135	117	86	72	130	35	26	59.8	116	68	48	44	89
68A	129	265	90	66	147	265	61	45	123.4	89	47	42	49	131
68B	143	290	85	63	161	290	60	44	144.0	87	48	39	40	152
68C	154	310	77	57	161	290	66	49	148.4	78	45	33	35	153
68D	154	310	77	57	158	285	56	41	150.6	78	39	39	58	148
69A	79	175	122	90	94	170	35	26	82.9	123	79	44	18	107
69B	93	200	104	77	108	195	53	39	88.5	111	66	45	30	108
69C	96	205	106	78	108	195	49	36	91.6	110	66	44	28	110
69D	102	215	103	76	114	205	42	31	97.6	104	59	45	31	111
70A	52	125	102	75	86	155	46	34	49.7	102	58	44	48	70
70B	43	110	126	93	53	95	37	27	42.6	133	51	82	84	54
70C	68	155	111	82	81	145	41	30	70.2	113	67	46	49	101
70D	104	220	100	74	106	190	49	36	106.2	102	57	45	38	120
71A	43	110	102	75	78	140	24	18	44.7	101	61	40	34	64
71B	29	85	114	84	56	100	62	46	28.7	119	14	105	106	1
71C	71	160	103	76	103	185	53	39	71.9	107	57	50	60	93
71D	107	225	88	65	94	170	58	43	107.5	89	53	36	31	119
72A	116	240	~ 92	~ 68	122	220	~ 52	~ 38	116.9	96	36	60	75	111
72B	138	280	84	62	144	260	60	44	139.3	88	34	54	70	131
72C	118	245	85	63	142	255	60	44	120.6	87	26	61	73	102
72D	132	270	85	63	144	260	54	40	133.8	89	35	54	72	126

^a Eyeball curve fit^b Tanh curve-fit procedure

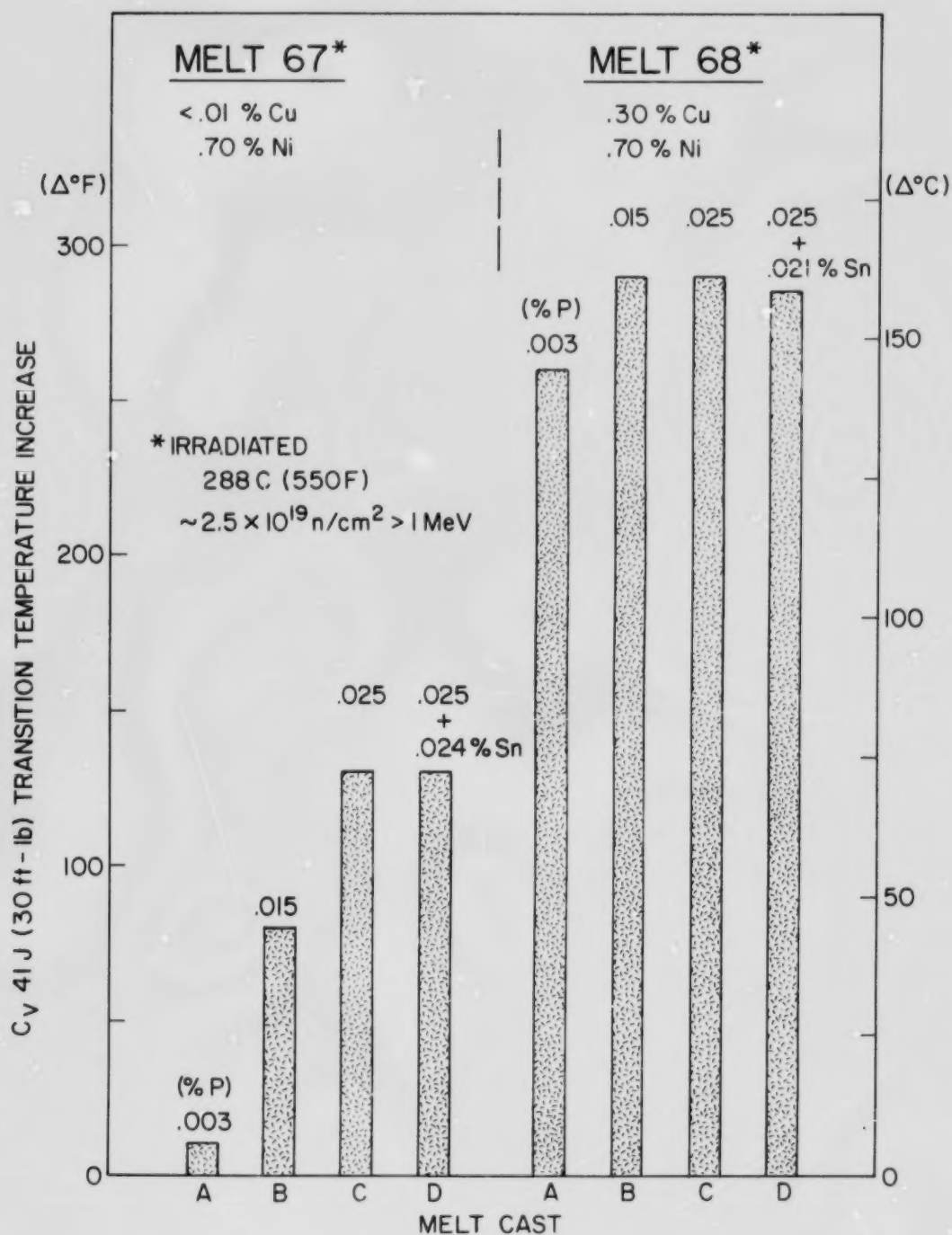


Fig. 9 C_v 41-J transition temperature increases observed for plates from melts 67 and 68 showing the dependence of the phosphorus influence on radiation sensitivity on copper content.

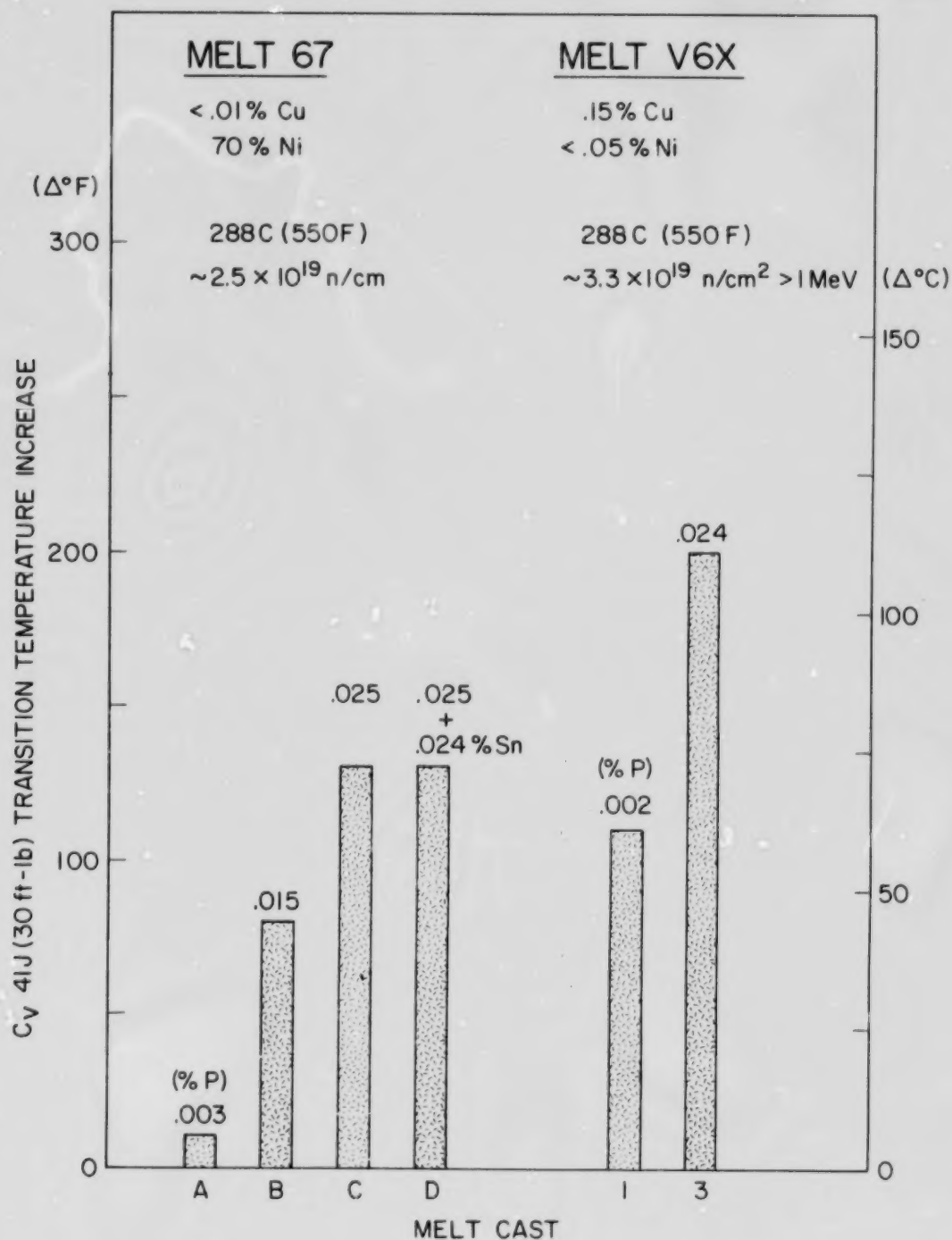


Fig. 10 C_v 41-J transition temperature increases observed for plates from melt 67 (A 533-B steel) and plates from melt V6X (A 302-B steel).

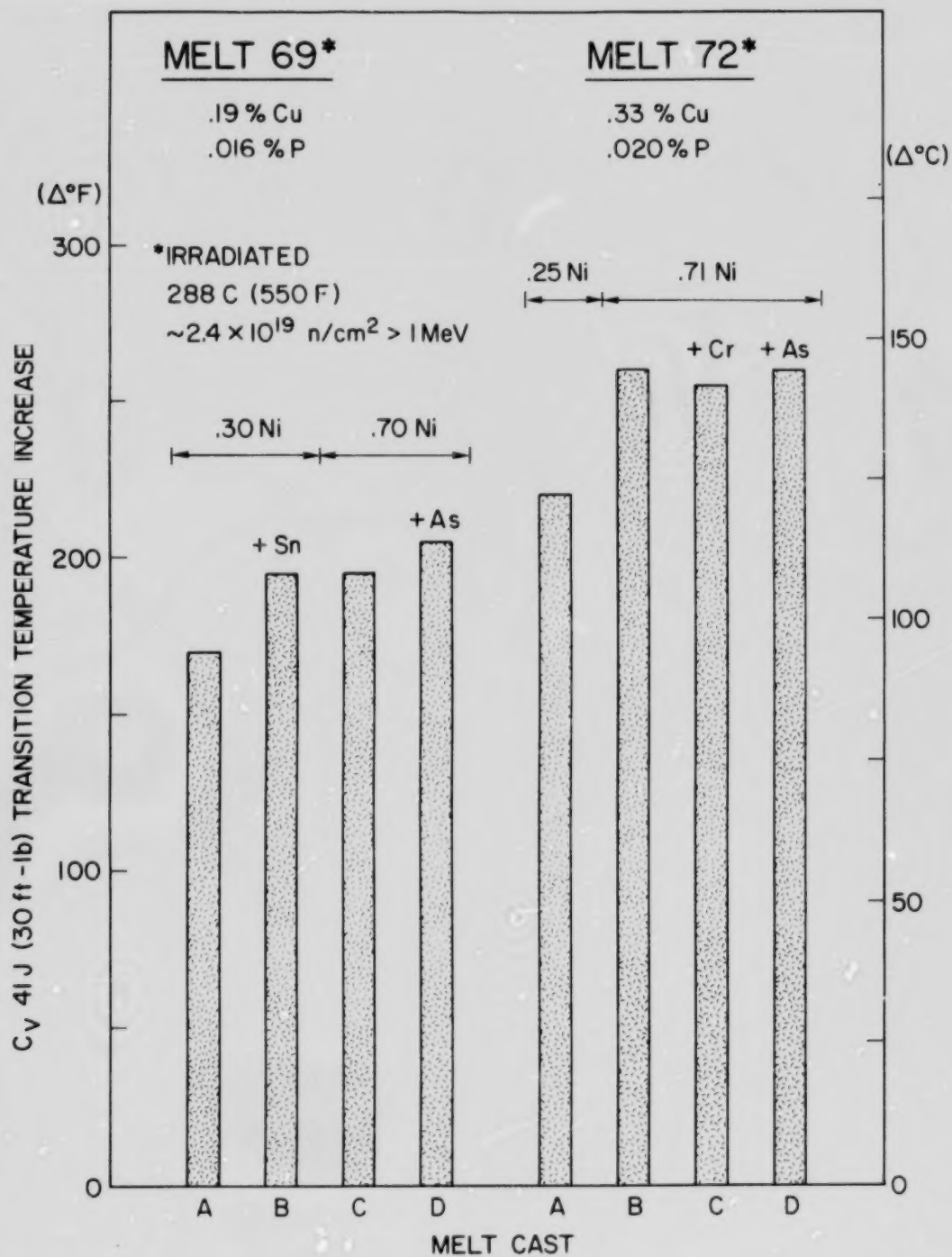


Fig. 11 C_v 41-J transition temperature increases observed for plates from melts 69 and 72.

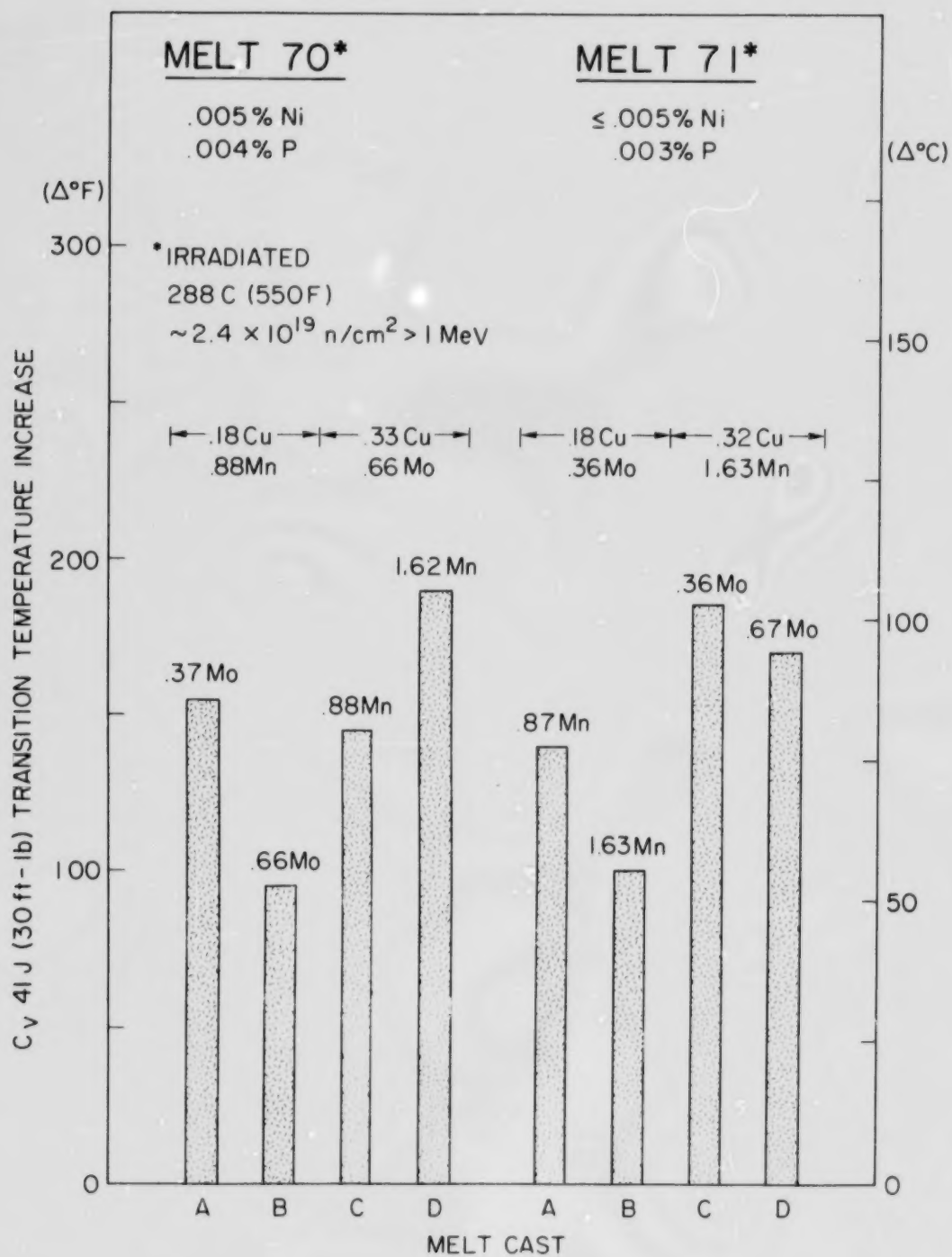


Fig. 12 C_v 41-J transition temperature increases observed for plates from melts 70 and 71.

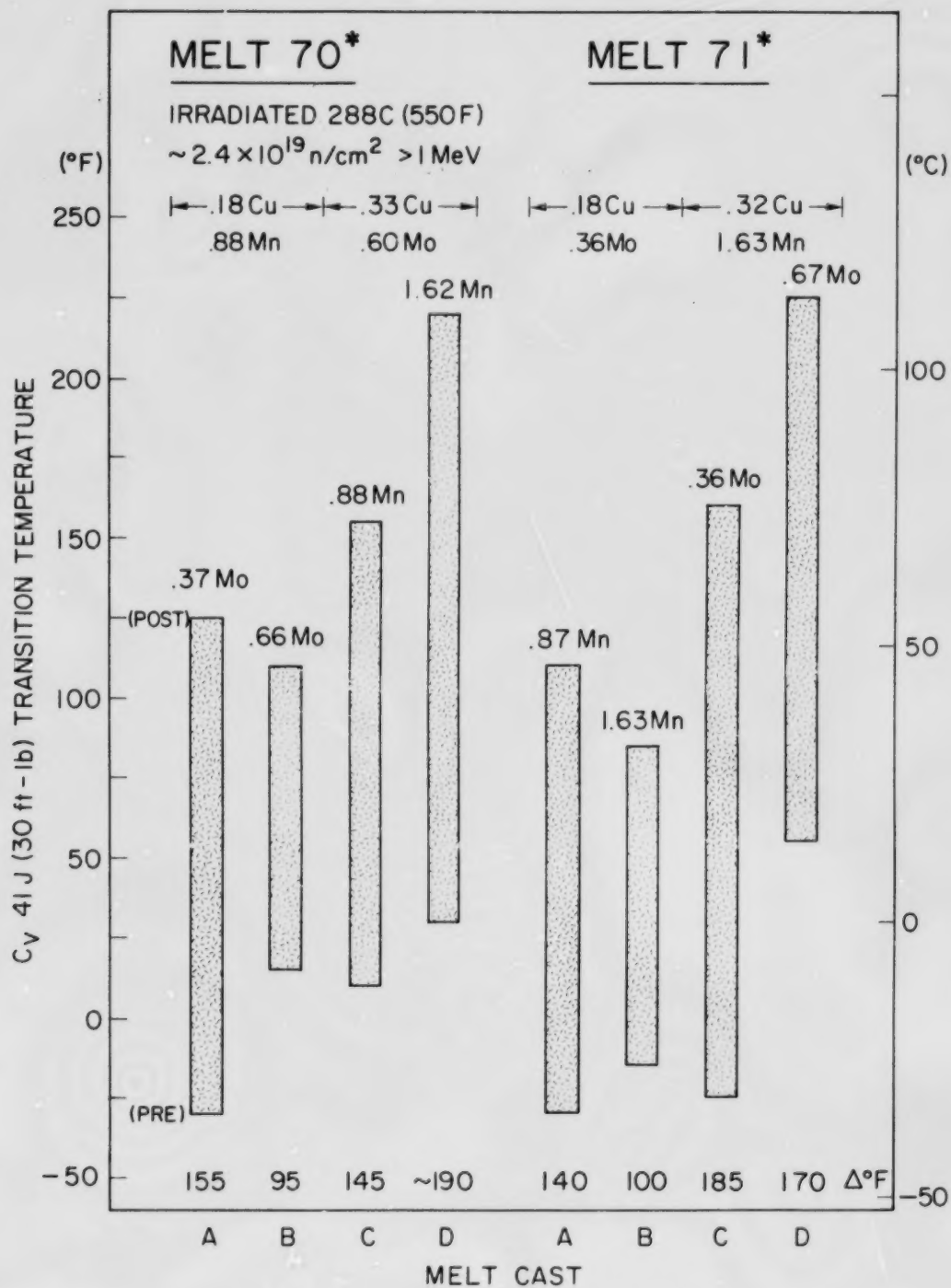


Fig. 13 Absolute C_v 41-J transition temperatures of plates from melts 70 and 71 before and after irradiation.

effect of tin impurities was most evident in the enhanced upper shelf energy reduction by irradiation. Addition of arsenic to the melt, on the other hand, did not produce a change in its apparent radiation resistance. In view of the aggregate results, the qualification of tin and arsenic, to be complete, will require a parallel study with low phosphorus, low copper content materials.

Consistent with the earlier findings which demonstrated the nickel/copper synergism (Ref. 2), a reinforcement of radiation sensitivity by an increase in nickel content from 0.4 to 0.7% Ni is evident in the data for the high copper, melt 72. On the other hand, a similar increase in nickel content in the intermediate copper content melt 69 did not produce a parallel effect. One major difference in composition between melt 72 (or melt 69) vs. the earlier melts (Ref. 2) is the phosphorus content, that is, 0.016% P (intermediate) vs. 0.005% P (low), respectively.

Alloying by 0.50% chromium did not alter the radiation resistance of melt 72. Current interest in potential chromium effects stems from prior comparisons of A 508-2 vs. A 533-B steels. The former, on balance, shows a lower susceptibility to 288°C radiation than A 533-B. This could be a reflection of the difference in chromium level, the difference in metal working history (forging vs. rolling), or some other factor. The present data, although limited, suggest that chromium alloying is not responsible for the lower radiation sensitivity of A 508-2. Preliminary irradiation data for melt 66 (copper/ chromium series, Table 1) support this tentative conclusion (Ref. 7).

6.2.3 Melts 70 and 71 (Copper/Manganese and Copper Molybdenum Series)

Findings for the materials depicting high-low manganese contents and high-low molybdenum contents coupled with intermediate (~ 0.18%) or high (0.33%) copper are illustrated in Fig. 12. In one case (intermediate copper), a high manganese content or separately, a high molybdenum content is found beneficial to irradiation resistance. In the second case (high copper), a high manganese level produced an adverse effect on radiation resistance. While no effect of a high vs. low molybdenum content is indicated for the high copper level material, a high molybdenum content did yield in a higher (preirradiation) 41-J transition temperature. For the intermediate copper material, this elevation served to negate the beneficial effect of the high molybdenum level on radiation resistance. That is, the final (as-irradiated) 41-J temperatures were comparable for high vs. low molybdenum materials containing an intermediate copper level (see Fig. 13). This, in turn, illustrates the value of the "total picture" from a reactor systems standpoint.

7. DISCUSSION

Determinations by this investigation clearly point up the need for a clear understanding of the dependence of impurity element effects on radiation resistance on alloying. Secondly, the study reveals that

interactions between impurity elements such as copper and phosphorus are possible in radiation sensitivity development and need further definition to avoid "technical surprises." From the standpoint of application, the move toward low copper content materials in reactor vessel construction, while having clear and positive benefits, carries a responsibility for recognizing that other influences could be activated in the absence of copper. Associated with this, the results demonstrate a continuing need for some degree of in-reactor surveillance for steels tailored for radiation resistance.

Qualitative information of the type provided by this study, can provide important guidance to the experimental isolation and modeling of radiation effects mechanisms. For one, the tie between phosphorus and copper revealed by the current investigation suggests a similarity of mechanisms, contrary to the earlier assumption of two independent mechanisms (precipitation vs. radiation-enhanced diffusion, along the lines of temper embrittlement). One possibility is the copper mechanism overwhelms the phosphorus mechanism or effectively "uses up" the type of defects upon which phosphorus mechanism depends. Another possibility is that the presence of copper passivates the phosphorus mechanism. Studies are in progress to clarify the roles of these elements (Ref. 7).

8. CONCLUSIONS

Primary observations from the investigations are:

- Phosphorus has an influence on the radiation sensitivity of steel at 288°C but its contribution is highly dependent on the steel's copper content. The detrimental influence of phosphorus on steel resistance is most pronounced when the copper content is low.
- A tin content of 0.021% can exert a detrimental influence on radiation resistance in 0.017% P steels. The influence is more evident from the upper shelf energy reduction than the 41-J transition elevation by irradiation.
- Arsenic content of 0.035% did not have an observable effect on the radiation sensitivity of plates containing ~ 0.020% P and > 0.18% Cu.
- Alloying with 0.50% chromium did not alter the radiation resistance of plates having a high copper content (~ 0.30%).
- For plates having an intermediate copper content (~ 0.18%), a high manganese content and a high molybdenum content can reduce radiation sensitivity. However, a comparable effect was not found in steels having a high copper content.

Determinations of this investigation are seen to reinforce previous evidence that important composition interactions exist in radiation sensitivity development. These most probably are responsible for a

large portion of the previously unexplained scatter found in individual, irradiation effects data banks.

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APPENDIX A

Laboratory Melt/Ingot Processing History

Melting

Each melt was made in a 181-kg (400-lb) vacuum induction furnace and was split to produce four (4) separate compositions. Each composition (45-kg or 100-lb quantity) was teemed into a 76-mm (3-in.) x 203-mm (8-in.) x 356-mm (14-in.) hot topped, cast iron ingot mold. The melt practice included vacuum carbon deoxidation (VCD).

Ingot Processing

The ingots were reheated and soaked at 1260°C (2300°F), hot-rolled (parallel to the ingot axis) to a nominal thickness of 63.5-mm (2.5-in.) cross rolled to a nominal thickness of 15.2 mm (0.6 in.) with a plate finishing temperature of 1060°C (1940°F) and air cooled to ambient.

Heat Treatment

The plates were heated to 899°C (1650°F) for one hour at temperature and air cooled. The plates were then reheated to 649°C (1200°F) for one hour (time-at-temperature) and water quenched. Each plate was then cut to remove one corner portion which served as source material for tension test specimen blanks. The plates, except for plate codes 70A and 71A, were then heated to 677°C (1250°F) for five hours and water quenched. Plate codes 70A and 71A were not reheat treated at 677°C but were tested in the 649°C tempered condition.

APPENDIX B

**Tabulations of Unirradiated-Condition
Charpy-V Notch Ductility Test Data**

Code 66A, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	177 (350)	145 (107)	1.98 (78)
3	1	-	71 (160)	133 (98)	1.88 (74)
7	1	-	-4 (25)	42 (31)	.71 (28)
9	1	-	13 (55)	66 (49)	1.09 (43)
11	1	-	204 (400)	155 (114)	1.93 (76)
13	1	-	143 (290)	153 (113)	2.34 (92)
15	1	-	-37 (-35)	7 (5)	.05 (2)
32	3	-	-7 (20)	31 (23)	.48 (19)
34	3	-	-18 (0)	14 (10)	.18 (7)
38	3	-	204 (400)	133 (98)	1.80 (71)
40	3	-	49 (120)	108 (80)	1.75 (69)
42	3	-	93 (200)	133 (98)	1.80 (71)
44	3	-	32 (90)	85 (63)	1.27 (50)
45	3	-	288 (550)	190 (140)	1.65 (65)

Code 66B, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	66 (150)	121 (89)	1.93 (76)
3	1	-	71 (160)	126 (93)	1.73 (68)
7	1	-	-4 (25)	45 (33)	.69 (27)
9	1	-	14 (57)	62 (46)	.97 (38)
11	1	-	204 (400)	141 (104)	2.01 (79)
13	1	-	143 (290)	138 (102)	1.93 (76)
15	1	-	-37 (-35)	8 (6)	.05 (2)
32	3	-	-7 (20)	39 (29)	.64 (25)
34	3	-	-18 (0)	30 (22)	.43 (17)
38	3	-	204 (400)	138 (102)	1.68 (66)
40	3	-	49 (120)	89 (66)	1.24 (49)
42	3	-	93 (200)	123 (91)	2.06 (81)
44	3	-	32 (90)	65 (48)	1.02 (40)
45	3	-	288 (550)	163 (120)	1.75 (69)

Code 66C, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	177 (350)	149 (110)	1.63 (64)
3	1	-	71 (160)	125 (92)	1.75 (69)
7	1	-	-4 (25)	38 (28)	.64 (25)
9	1	-	13 (55)	56 (41)	.86 (34)
11	1	-	204 (400)	153 (113)	2.06 (81)
13	1	-	143 (290)	146 (108)	1.63 (64)
15	1	-	-37 (-35)	11 (8)	.15 (6)
32	3	-	-1 (30)	52 (38)	.79 (31)
34	3	-	-18 (0)	28 (21)	.41 (16)
38	3	-	204 (400)	130 (96)	1.91 (75)
40	3	-	49 (120)	88 (65)	1.42 (56)
42	3	-	93 (200)	130 (96)	1.83 (72)
44	3	-	32 (90)	89 (66)	1.37 (54)
45	3	-	288 (550)	165 (122)	1.70 (67)

Code 66D, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	-12 (10)	42 (31)	.58 (23)
3	1	-	71 (160)	141 (104)	1.68 (66)
7	1	-	-4 (25)	52 (38)	.79 (31)
9	1	-	13 (56)	68 (50)	1.04 (41)
11	1	-	204 (400)	138 (102)	2.01 (79)
13	1	-	143 (290)	148 (109)	1.91 (75)
15	1	-	-37 (-35)	24 (18)	.30 (12)
32	3	-	43 (110)	114 (84)	1.57 (62)
34	3	-	-18 (0)	33 (24)	.43 (17)
38	3	-	204 (400)	140 (103)	1.91 (75)
40	3	-	49 (120)	89 (66)	1.22 (48)
42	3	-	93 (200)	138 (102)	1.91 (75)
44	3	-	32 (90)	110 (81)	1.52 (60)
45	3	-	288 (550)	144 (106)	1.91 (75)

Code 67A, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	24 (75)	81 (60)	1.32 (52)
3	1	-	-7 (20)	27 (20)	.58 (23)
5	1	-	-40 (-40)	14 (10)	.23 (9)
7	1	-	-23 (-10)	20 (15)	**** (***)
11	1	-	143 (290)	167 (123)	2.16 (85)
13	1	-	204 (400)	152 (112)	**** (***)
15	1	-	24 (75)	75 (55)	1.24 (49)
31	3	-	10 (50)	58 (43)	.94 (37)
33	3	-	-18 (0)	42 (31)	.74 (29)
35	3	-	4 (40)	61 (45)	.99 (39)
37	3	-	60 (140)	130 (96)	1.96 (77)
39	3	-	93 (200)	141 (104)	2.06 (81)
40	3	-	288 (550)	296 (218)	**** (***)
41	3	-	-7 (20)	38 (28)	.61 (24)
43	3	-	288 (550)	260 (192)	1.55 (61)
45	3	-	177 (350)	190 (140)	2.21 (87)

Code 67B, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	24 (75)	73 (54)	**** (***)
3	1	-	-7 (20)	35 (26)	.56 (22)
5	1	-	-23 (-10)	30 (22)	.43 (17)
7	1	-	-40 (-40)	9 (7)	.18 (7)
11	1	-	143 (290)	172 (127)	2.26 (89)
13	1	-	204 (400)	160 (118)	2.11 (83)
15	1	-	24 (75)	87 (64)	1.30 (51)
31	3	-	60 (140)	92 (68)	1.45 (57)
33	3	-	4 (40)	52 (38)	.84 (33)
35	3	-	-18 (0)	27 (20)	.46 (18)
37	3	-	66 (150)	108 (80)	1.60 (63)
39	3	-	93 (200)	144 (106)	2.06 (81)
40	3	-	260 (500)	169 (125)	**** (***)
41	3	-	-1 (30)	43 (32)	.71 (28)
43	3	-	177 (350)	157 (116)	2.18 (86)

Code 67C, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	24 (75)	88 (65)	1.37 (54)
3	1	-	-40 (-40)	16 (12)	.23 (9)
5	1	-	204 (400)	149 (110)	2.06 (81)
7	1	-	-18 (0)	50 (37)	.79 (31)
9	1	-	60 (140)	136 (100)	1.91 (75)
11	1	-	132 (270)	149 (110)	2.03 (80)
13	1	-	288 (550)	160 (118)	2.08 (82)
31	3	-	-18 (0)	38 (28)	**** (***)
33	3	-	160 (320)	150 (111)	**** (***)
35	3	-	4 (40)	73 (54)	1.09 (43)
37	3	-	-62 (-80)	8 (6)	.10 (4)
39	3	-	93 (200)	146 (108)	2.18 (86)
40	3	-	288 (550)	156 (115)	**** (***)
41	3	-	49 (120)	113 (83)	1.68 (66)
45	3	-	24 (75)	84 (62)	1.24 (49)

Code 67D, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	24 (75)	79 (58)	1.22 (48)
3	1	-	-40 (-40)	9 (7)	.13 (5)
5	1	-	204 (400)	155 (114)	1.93 (76)
7	1	-	-18 (0)	39 (29)	.66 (26)
9	1	-	60 (140)	110 (81)	1.65 (65)
11	1	-	132 (270)	155 (114)	2.13 (84)
13	1	-	288 (550)	212 (156)	2.08 (82)
31	3	-	182 (360)	146 (108)	2.21 (87)
33	3	-	-18 (0)	39 (29)	**** (***)
35	3	-	4 (40)	56 (41)	.86 (34)
37	3	-	-51 (-60)	9 (7)	.10 (4)
39	3	-	93 (200)	138 (102)	2.06 (81)
40	3	-	288 (550)	188 (139)	**** (***)
41	3	-	49 (120)	91 (67)	1.42 (56)
45	3	-	24 (75)	76 (56)	1.17 (46)

Code 68A, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	60 (140)	117 (86)	1.65 (65)
3	1	-	-40 (-40)	35 (26)	.46 (18)
7	1	-	-18 (0)	46 (34)	.69 (27)
9	1	-	93 (200)	149 (110)	2.18 (86)
11	1	-	4 (40)	43 (32)	.74 (29)
13	1	-	288 (550)	152 (112)	2.29 (90)
15	1	-	21 (70)	79 (58)	1.24 (49)
31	3	-	-7 (20)	46 (34)	.81 (32)
33	3	-	4 (40)	68 (50)	1.02 (40)
35	3	-	32 (90)	89 (66)	1.37 (54)
39	3	-	143 (290)	149 (110)	2.13 (84)
41	3	-	204 (400)	155 (114)	2.24 (88)
43	3	-	-34 (-30)	28 (21)	**** (***)
45	3	-	-62 (-80)	8 (6)	.10 (4)

Code 68B, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
3	1	-	-40 (-40)	14 (10)	.20 (8)
5	1	-	60 (140)	127 (94)	**** (***)
7	1	-	-18 (0)	38 (28)	.58 (23)
9	1	-	93 (200)	149 (110)	2.21 (87)
11	1	-	4 (40)	62 (46)	.97 (38)
13	1	-	288 (550)	191 (141)	1.91 (75)
15	1	-	38 (100)	100 (74)	1.50 (59)
31	3	-	-7 (20)	46 (34)	.71 (28)
33	3	-	4 (40)	58 (43)	1.45 (57)
35	3	-	-57 (-70)	8 (6)	**** (***)
37	3	-	28 (82)	71 (52)	1.12 (44)
39	3	-	143 (290)	144 (106)	2.16 (85)
41	3	-	204 (400)	144 (106)	2.21 (87)
43	3	-	-34 (-30)	31 (23)	.48 (19)
45	3	-	288 (550)	155 (114)	**** (***)

Code 68C, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	288 (550)	152 (112)	2.06 (81)
3	1	-	-40 (-40)	14 (10)	.18 (7)
5	1	-	60 (140)	125 (92)	**** (***)
7	1	-	-18 (0)	43 (32)	.64 (25)
9	1	-	93 (200)	146 (108)	2.01 (79)
11	1	-	4 (40)	60 (44)	.89 (35)
13	1	-	32 (90)	92 (68)	**** (***)
31	3	-	-7 (20)	41 (30)	.64 (25)
33	3	-	4 (40)	52 (38)	.79 (31)
37	3	-	28 (82)	76 (56)	1.14 (45)
39	3	-	143 (290)	141 (104)	2.11 (83)
41	3	-	204 (400)	144 (106)	2.11 (83)
43	3	-	-34 (-30)	22 (16)	.33 (13)

Code 68D, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	288 (550)	171 (126)	2.16 (85)
3	1	-	-40 (-40)	22 (16)	.30 (12)
5	1	-	60 (140)	111 (82)	**** (***)
7	1	-	-18 (0)	30 (22)	.41 (16)
9	1	-	93 (200)	136 (100)	1.83 (72)
11	1	-	4 (40)	57 (42)	.84 (33)
31	3	-	-7 (20)	35 (26)	.53 (21)
33	3	-	4 (40)	42 (31)	.69 (27)
35	3	-	21 (70)	76 (56)	**** (***)
37	3	-	25 (77)	84 (62)	1.19 (47)
39	3	-	143 (290)	133 (98)	1.98 (78)
41	3	-	204 (400)	133 (98)	2.01 (79)
43	3	-	-34 (-30)	22 (16)	.30 (12)
45	3	-	288 (550)	149 (110)	1.98 (78)

Code 69A, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	204 (400)	152 (112)	**** (***)
3	1	-	60 (140)	113 (83)	**** (***)
5	1	-	60 (140)	133 (98)	**** (***)
7	1	-	-18 (0)	43 (32)	**** (***)
9	1	-	93 (200)	163 (120)	**** (***)
11	1	-	4 (40)	69 (51)	**** (***)
15	1	-	38 (100)	99 (73)	**** (***)
34	3	-	4 (40)	26 (19)	**** (***)
36	3	-	-40 (-40)	16 (12)	**** (***)
38	3	-	24 (75)	81 (60)	**** (***)
40	3	-	143 (290)	164 (121)	**** (***)
42	3	-	-12 (10)	45 (33)	**** (***)
44	3	-	182 (360)	155 (114)	**** (***)

Code 69B, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	204 (400)	164 (121)	**** (***)
5	1	-	60 (140)	138 (102)	**** (***)
7	1	-	-18 (0)	38 (28)	**** (***)
9	1	-	93 (200)	149 (110)	**** (***)
11	1	-	4 (40)	75 (55)	**** (***)
15	1	-	38 (100)	114 (84)	**** (***)
34	3	-	4 (40)	66 (49)	**** (***)
36	3	-	-12 (10)	37 (27)	**** (***)
38	3	-	24 (75)	87 (64)	**** (***)
40	3	-	143 (290)	160 (118)	**** (***)
42	3	-	182 (360)	146 (108)	**** (***)
44	3	-	-40 (-40)	16 (12)	**** (***)

Code 69C, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	160 (320)	157 (116)	**** (***)
3	1	-	60 (140)	126 (93)	**** (***)
5	1	-	60 (140)	133 (98)	**** (***)
7	1	-	-18 (0)	26 (19)	**** (***)
9	1	-	93 (200)	155 (114)	**** (***)
11	1	-	4 (40)	56 (41)	**** (***)
15	1	-	204 (400)	155 (114)	**** (***)
32	3	-	-12 (10)	52 (38)	**** (***)
36	3	-	-40 (-40)	15 (11)	**** (***)
38	3	-	24 (75)	89 (66)	**** (***)
40	3	-	143 (290)	144 (106)	**** (***)
42	3	-	204 (400)	164 (121)	**** (***)

Code 69D, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	160 (320)	149 (110)	**** (***)
3	1	-	60 (140)	130 (96)	**** (***)
5	1	-	60 (140)	100 (74)	**** (***)
7	1	-	-18 (0)	41 (30)	**** (***)
9	1	-	93 (200)	149 (110)	**** (***)
11	1	-	4 (40)	56 (41)	**** (***)
15	1	-	204 (400)	141 (104)	**** (***)
32	3	-	-40 (-40)	9 (7)	**** (***)
34	3	-	4 (40)	62 (46)	**** (***)
36	3	-	-12 (10)	43 (32)	**** (***)
38	3	-	24 (75)	95 (70)	**** (***)
40	3	-	143 (290)	137 (101)	**** (***)
42	3	-	204 (400)	148 (109)	**** (***)

Code 70A, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	-57 (-70)	14 (10)	.18 (7)
3	1	-	-18 (0)	60 (44)	.91 (36)
7	1	-	27 (80)	115 (85)	1.80 (71)
9	1	-	-40 (-40)	43 (32)	.64 (25)
11	1	-	-1 (30)	89 (66)	1.47 (58)
13	1	-	204 (400)	144 (106)	2.01 (79)
15	1	-	121 (250)	141 (104)	2.03 (80)
10	1	-	-7 (20)	76 (56)	1.19 (47)
32	3	-	4 (40)	72 (53)	1.30 (51)
34	3	-	21 (70)	98 (72)	1.52 (60)
40	3	-	-23 (-10)	42 (31)	.66 (26)
42	3	-	49 (120)	117 (86)	1.91 (75)
44	3	-	-40 (-40)	34 (25)	.58 (23)
45	3	-	160 (320)	150 (111)	2.26 (89)
41	3	-	93 (200)	133 (98)	2.03 (80)

Code 70B, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	204 (400)	163 (120)	1.68 (66)
3	1	-	-12 (10)	46 (34)	.76 (30)
7	1	-	27 (80)	103 (76)	1.60 (63)
9	1	-	-23 (-10)	31 (23)	.51 (20)
11	1	-	-1 (30)	49 (36)	.81 (32)
13	1	-	204 (400)	235 (173)	1.75 (69)
15	1	-	149 (300)	155 (114)	2.34 (92)
32	3	-	4 (40)	53 (39)	.91 (36)
34	3	-	21 (70)	71 (52)	1.19 (47)
40	3	-	-23 (-10)	8 (6)	.13 (5)
42	3	-	49 (120)	94 (69)	1.55 (61)
44	3	-	-18 (0)	28 (21)	.48 (19)
45	3	-	160 (320)	163 (120)	2.18 (86)
41	3	-	93 (200)	148 (109)	2.16 (85)

Code 70C, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	288 (550)	146 (108)	2.03 (80)
3	1	-	-12 (10)	45 (33)	.74 (29)
7	1	-	27 (80)	111 (82)	1.65 (65)
9	1	-	-29 (-20)	19 (14)	.28 (11)
11	1	-	-1 (30)	58 (43)	.91 (36)
13	1	-	204 (400)	187 (138)	1.60 (63)
15	1	-	16 (60)	89 (66)	1.42 (56)
32	3	-	16 (60)	73 (54)	1.30 (51)
34	3	-	-7 (20)	46 (34)	.71 (28)
40	3	-	-23 (-10)	14 (10)	.23 (9)
42	3	-	204 (400)	155 (114)	2.03 (80)
44	3	-	49 (120)	136 (100)	1.73 (68)
45	3	-	160 (320)	152 (112)	2.16 (85)
41	3	-	93 (200)	150 (111)	2.36 (93)

Code 70D, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	-29 (-20)	4 (3)	.15 (6)
3	1	-	-12 (10)	42 (31)	.94 (37)
7	1	-	27 (80)	71 (52)	1.04 (41)
9	1	-	71 (160)	114 (84)	1.60 (63)
11	1	-	-1 (30)	53 (39)	.84 (33)
13	1	-	204 (400)	152 (112)	2.11 (83)
15	1	-	-7 (20)	45 (33)	.64 (25)
32	3	-	21 (70)	49 (36)	.79 (31)
34	3	-	-7 (20)	19 (14)	.33 (13)
40	3	-	-18 (0)	16 (12)	.28 (11)
42	3	-	7 (45)	49 (36)	.74 (29)
44	3	-	49 (120)	96 (71)	1.37 (54)
45	3	-	160 (320)	148 (109)	1.85 (73)
41	3	-	93 (200)	136 (100)	2.11 (83)

Code 71A, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	-26 (-15)	54 (40)	.86 (34)
3	1	-	-40 (-40)	39 (29)	.64 (25)
7	1	-	27 (80)	113 (83)	1.78 (70)
9	1	-	-59 (-75)	8 (6)	.10 (4)
11	1	-	-1 (30)	72 (53)	1.32 (52)
13	1	-	204 (400)	136 (100)	1.78 (70)
15	1	-	-54 (-65)	3 (2)	0.00 (0)
32	3	-	204 (400)	119 (88)	2.01 (79)
34	3	-	-40 (-40)	4 (3)	0.00 (0)
40	3	-	-23 (-10)	57 (42)	.91 (36)
42	3	-	54 (130)	126 (93)	2.01 (79)
44	3	-	-40 (-40)	43 (32)	.74 (29)
45	3	-	160 (320)	126 (93)	2.08 (82)
41	3	-	93 (200)	126 (93)	1.98 (78)

Code 71B, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	-18 (0)	68 (50)	1.04 (41)
3	1	-	-40 (-40)	20 (15)	.36 (14)
7	1	-	27 (80)	103 (76)	1.80 (71)
9	1	-	-59 (-75)	7 (5)	0.00 (0)
11	1	-	-1 (30)	73 (54)	1.24 (49)
13	1	-	204 (400)	184 (136)	2.16 (85)
15	1	-	-29 (-20)	45 (33)	.71 (28)
32	3	-	-40 (-40)	18 (13)	.28 (11)
34	3	-	54 (130)	133 (98)	2.01 (79)
40	3	-	-23 (-10)	49 (36)	.81 (32)
42	3	-	93 (200)	168 (124)	2.26 (89)
44	3	-	204 (400)	198 (146)	1.83 (72)
45	3	-	160 (320)	168 (124)	2.29 (90)

Code 71C, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	-18 (0)	60 (44)	.91 (36)
3	1	-	-40 (-40)	26 (19)	.38 (15)
7	1	-	27 (80)	108 (80)	1.65 (65)
9	1	-	149 (300)	160 (118)	1.85 (73)
11	1	-	-1 (30)	84 (62)	1.42 (56)
13	1	-	204 (400)	201 (148)	1.80 (71)
15	1	-	49 (120)	153 (113)	2.36 (93)
32	3	-	-40 (-40)	28 (21)	.38 (15)
34	3	-	54 (130)	163 (120)	2.51 (99)
40	3	-	-23 (-10)	56 (41)	.89 (35)
42	3	-	-59 (-75)	7 (5)	.08 (3)
44	3	-	204 (400)	195 (144)	1.93 (76)
45	3	-	160 (320)	149 (110)	1.80 (71)
41	3	-	93 (200)	150 (111)	2.11 (83)

Code 71D, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	288 (550)	165 (122)	2.01 (79)
3	1	-	49 (120)	83 (61)	1.30 (51)
7	1	-	27 (80)	57 (42)	.89 (35)
9	1	-	149 (300)	142 (105)	2.01 (79)
11	1	-	-1 (30)	28 (21)	.43 (17)
13	1	-	204 (400)	149 (110)	2.34 (92)
15	1	-	77 (170)	123 (91)	2.01 (79)
32	3	-	54 (130)	89 (66)	1.27 (50)
34	3	-	16 (60)	41 (30)	.76 (30)
40	3	-	-18 (0)	14 (10)	.25 (10)
44	3	-	204 (400)	157 (116)	2.34 (92)
45	3	-	160 (320)	144 (106)	1.78 (70)
41	3	-	93 (200)	132 (97)	2.18 (86)

Code 72A, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	160 (320)	144 (106)	**** (***)
3	1	-	-40 (-40)	14 (10)	**** (***)
5	1	-	60 (140)	103 (76)	**** (***)
7	1	-	-18 (0)	45 (33)	**** (***)
9	1	-	93 (200)	146 (108)	**** (***)
11	1	-	4 (40)	69 (51)	**** (***)
32	3	-	-12 (10)	19 (14)	**** (***)
34	3	-	4 (40)	46 (34)	**** (***)
38	3	-	24 (75)	81 (60)	**** (***)
40	3	-	143 (290)	130 (96)	**** (***)
42	3	-	204 (400)	155 (114)	**** (***)
44	3	-	60 (140)	117 (86)	**** (***)
45	3	-	-7 (20)	39 (29)	**** (***)

Code 72B, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	160 (320)	146 (108)	**** (***)
3	1	-	-40 (-40)	14 (10)	**** (***)
5	1	-	26 (78)	84 (62)	**** (***)
7	1	-	-18 (0)	30 (22)	**** (***)
9	1	-	93 (200)	144 (106)	**** (***)
11	1	-	4 (40)	66 (49)	**** (***)
15	1	-	204 (400)	155 (114)	**** (***)
32	3	-	60 (140)	110 (81)	**** (***)
36	3	-	-12 (10)	38 (28)	**** (***)
38	3	-	24 (75)	81 (60)	**** (***)
40	3	-	143 (290)	137 (101)	**** (***)
42	3	-	204 (400)	160 (118)	**** (***)
44	3	-	4 (40)	56 (41)	**** (***)

Code 72C, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	160 (320)	144 (106)	**** (***)
3	1	-	-40 (-40)	33 (24)	**** (***)
5	1	-	60 (140)	123 (91)	**** (***)
7	1	-	-18 (0)	54 (40)	**** (***)
9	1	-	93 (200)	144 (106)	**** (***)
11	1	-	4 (40)	76 (56)	**** (***)
32	3	-	-23 (-10)	31 (23)	**** (***)
34	3	-	4 (40)	57 (42)	**** (***)
36	3	-	-46 (-50)	19 (14)	**** (***)
38	3	-	24 (75)	95 (70)	**** (***)
40	3	-	143 (290)	130 (96)	**** (***)
42	3	-	204 (400)	149 (110)	**** (***)

Code 72D, Unirradiated

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
1	1	-	160 (320)	136 (100)	**** (***)
3	1	-	-40 (-40)	11 (8)	**** (***)
5	1	-	60 (140)	123 (91)	**** (***)
7	1	-	-18 (0)	43 (32)	**** (***)
9	1	-	93 (200)	144 (106)	**** (***)
11	1	-	4 (40)	57 (42)	**** (***)
15	1	-	32 (90)	92 (68)	**** (***)
32	3	-	-12 (10)	33 (24)	**** (***)
34	3	-	4 (40)	56 (41)	**** (***)
38	3	-	24 (75)	87 (64)	**** (***)
40	3	-	143 (290)	119 (88)	**** (***)
42	3	-	204 (400)	146 (108)	**** (***)
44	3	-	132 (270)	130 (96)	**** (***)
45	3	-	-40 (-40)	33 (24)	**** (***)
33	3	-	-18 (0)	39 (29)	**** (***)

APPENDIX C

Computer Curve Fitting of Unirradiated-Condition Charpy-V Notch Ductility Test Data

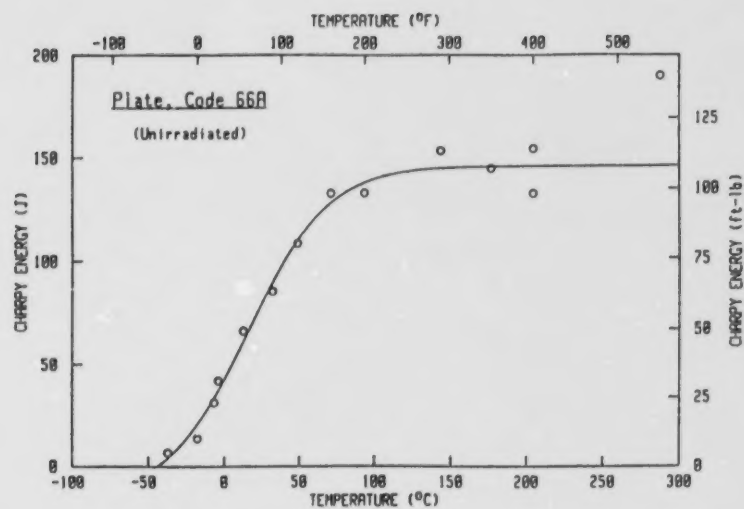


Fig. C-1 Charpy-V data for plate code 66A.

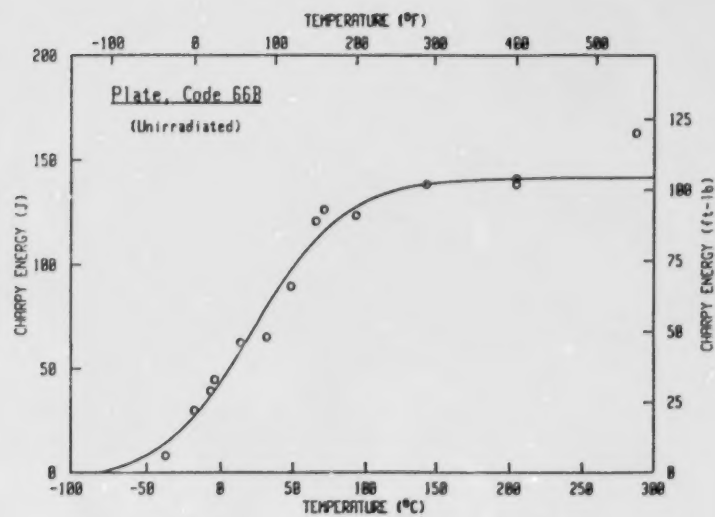


Fig. C-2 Charpy-V data for plate code 66B.

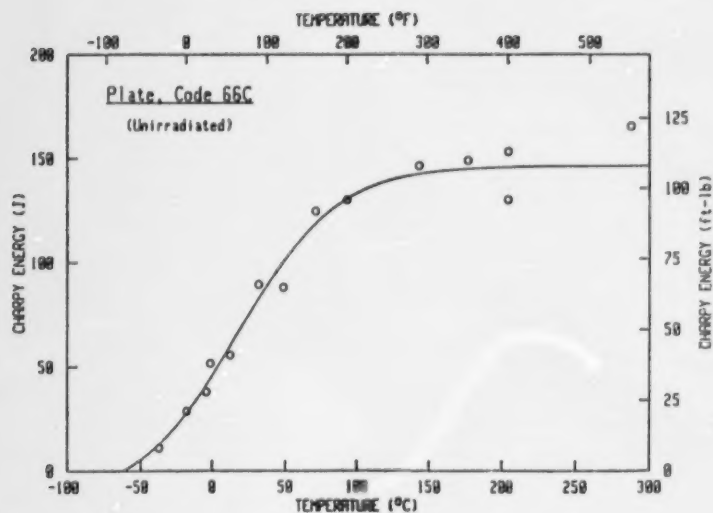


Fig. C-3 Charpy-V data for plate code 66C.

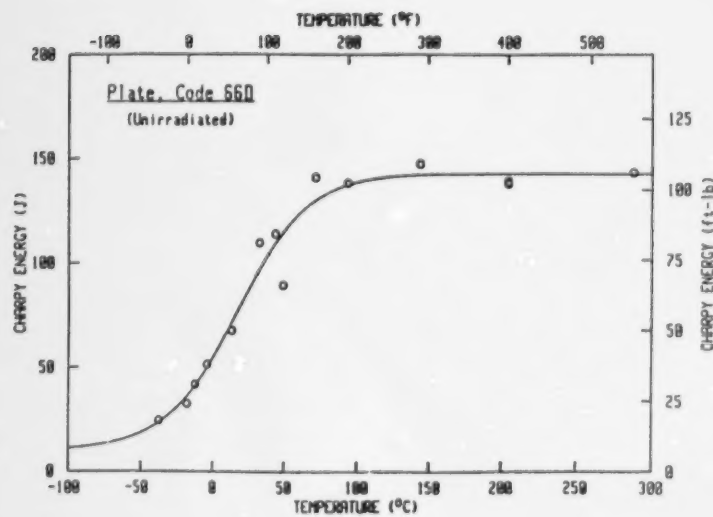


Fig. C-4 Charpy-V data for plate code 66D.

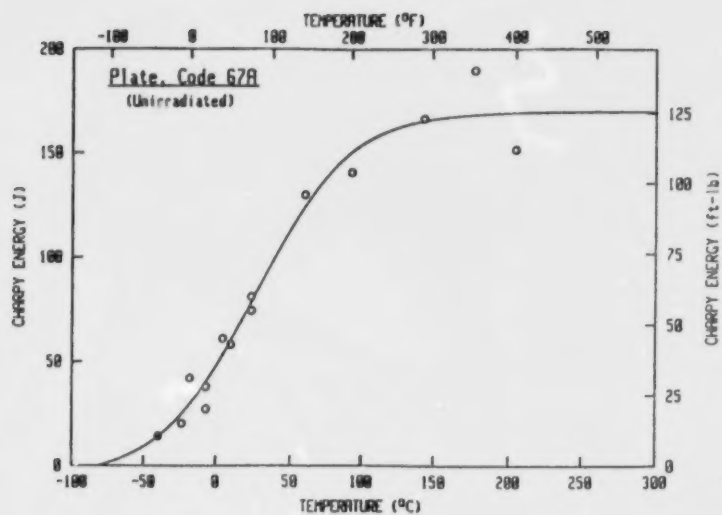


Fig. C-5 Charpy-V data for plate code 67A.

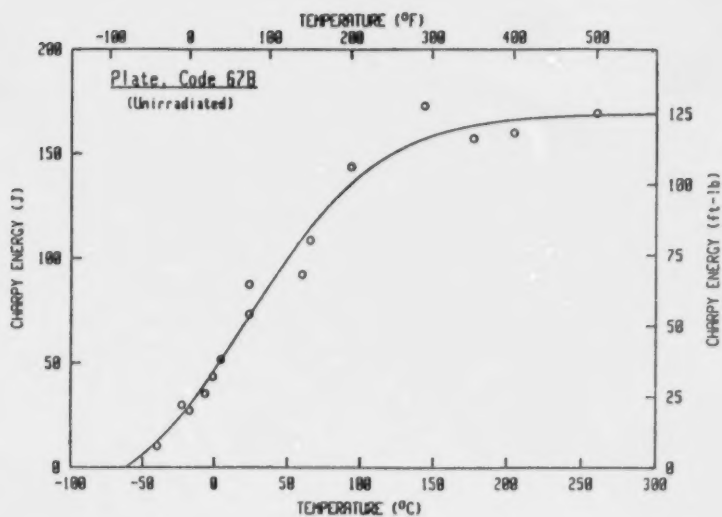


Fig. C-6 Charpy-V data for plate code 67B.

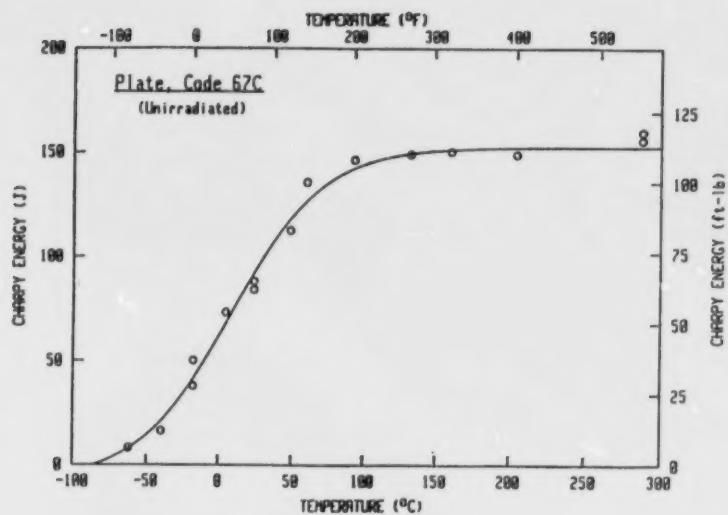


Fig. C-7 Charpy-V data for plate code 67C.

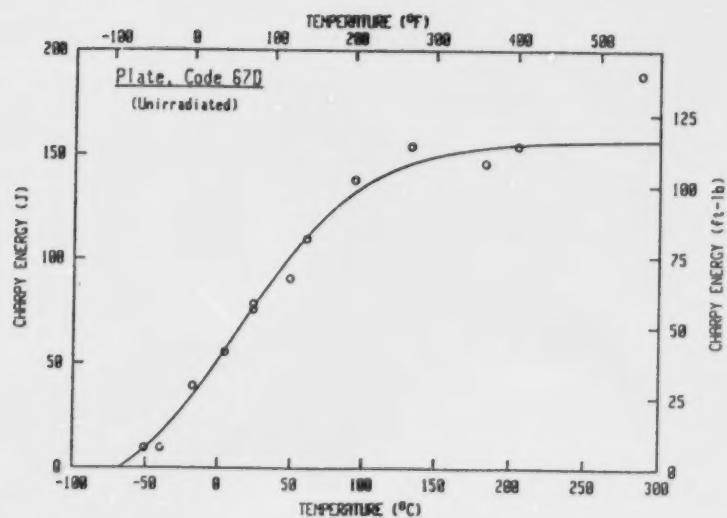


Fig. C-8 Charpy-V data for plate code 67D.

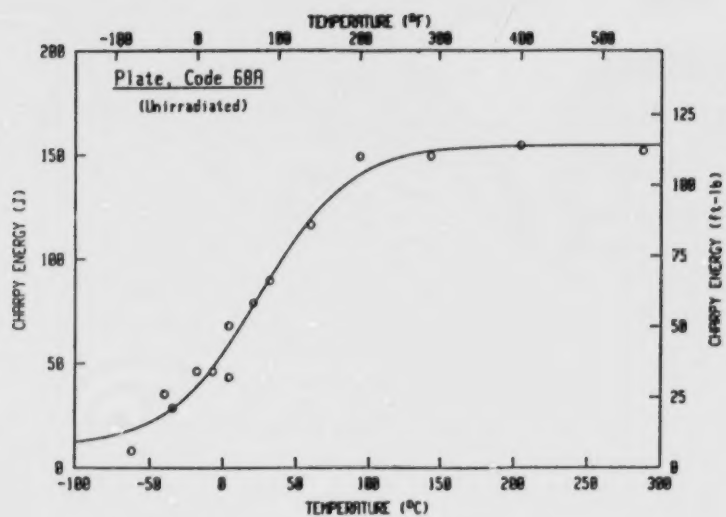


Fig. C-9 Charpy-V data for plate code 68A.

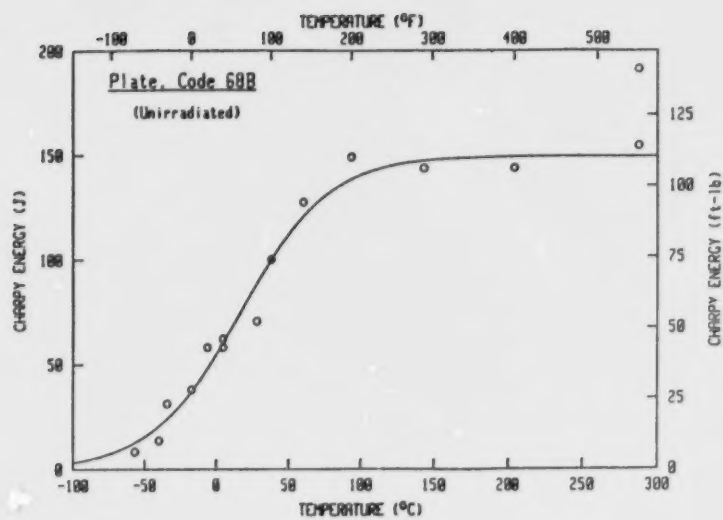


Fig. C-10 Charpy-V data for plate code 68B.

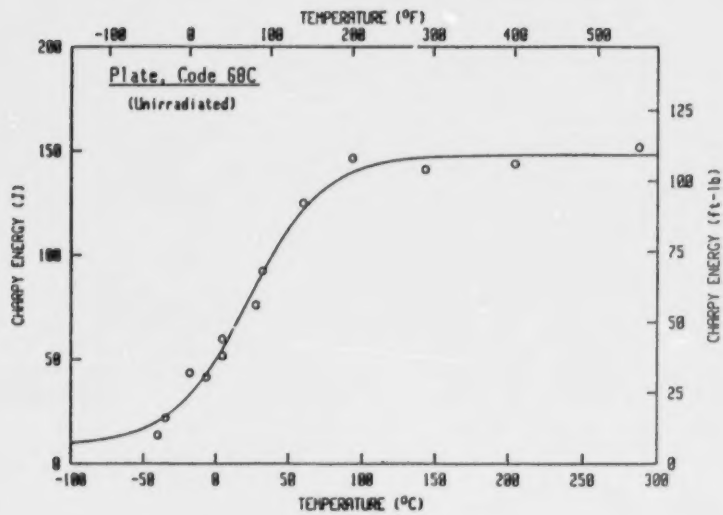


Fig. C-11 Charpy-V data for plate code 68C.

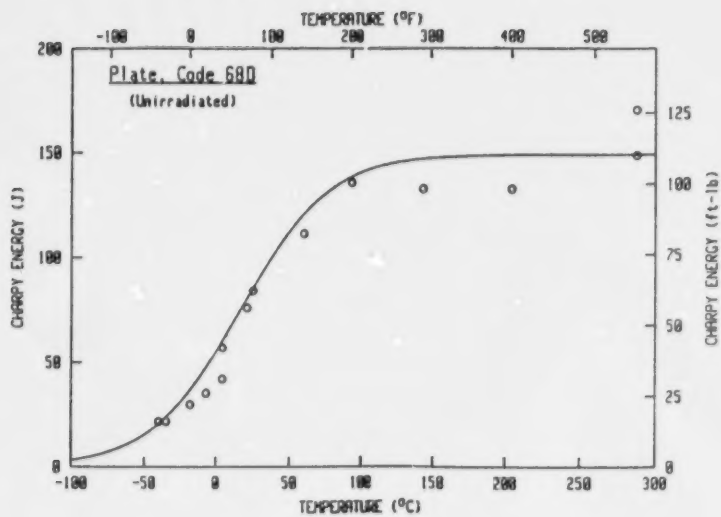


Fig. C-12 Charpy-V data for plate code 68D.

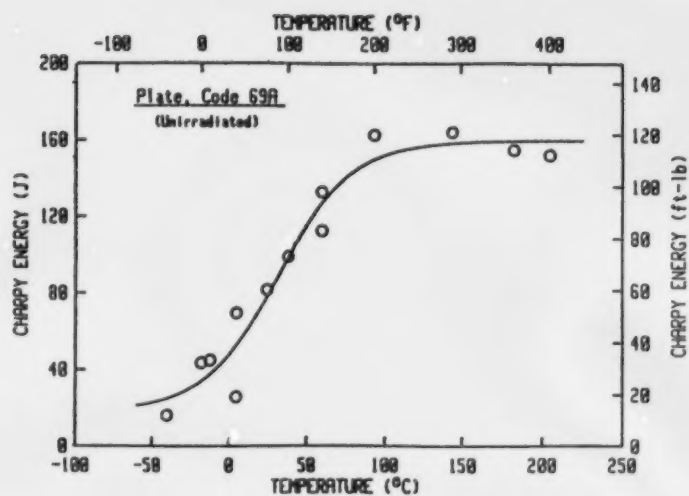


Fig. C-13 Charpy-V data for plate code 69A.

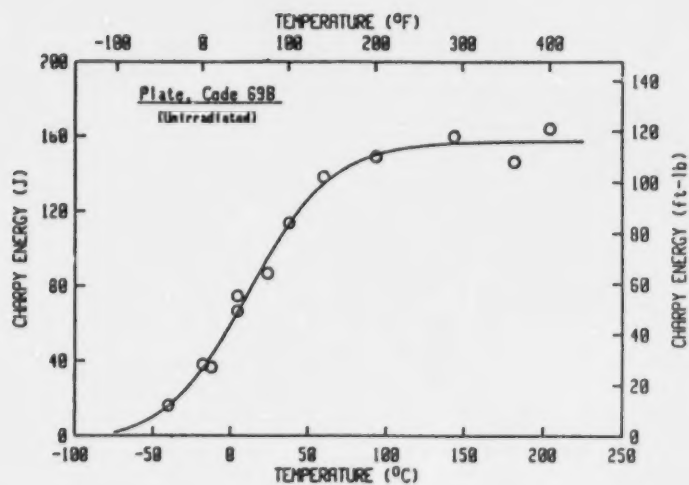


Fig. C-14 Charpy-V data for plate code 69B.

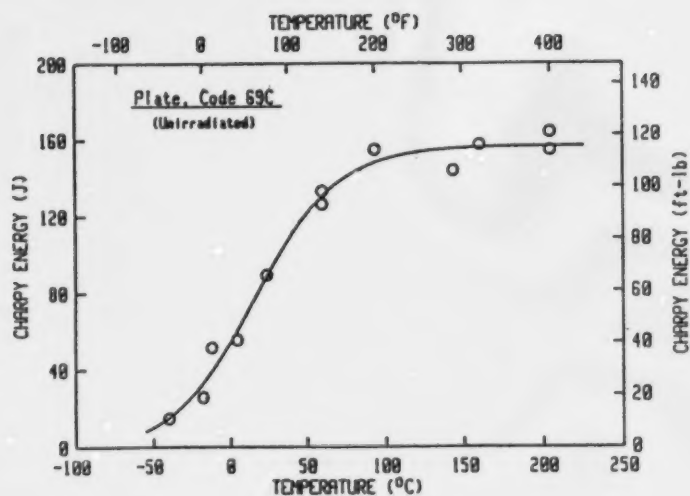


Fig. C-15 Charpy-V data for plate code 69C.

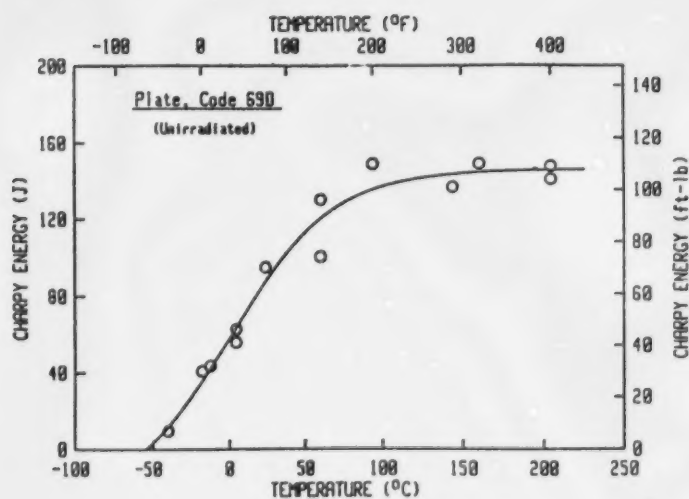


Fig. C-16 Charpy-V data for plate code 69D.

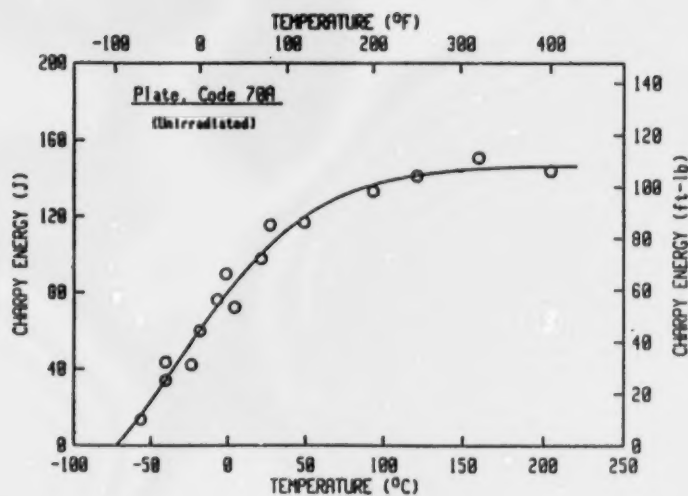


Fig. C-17 Charpy-V data for plate code 70A.

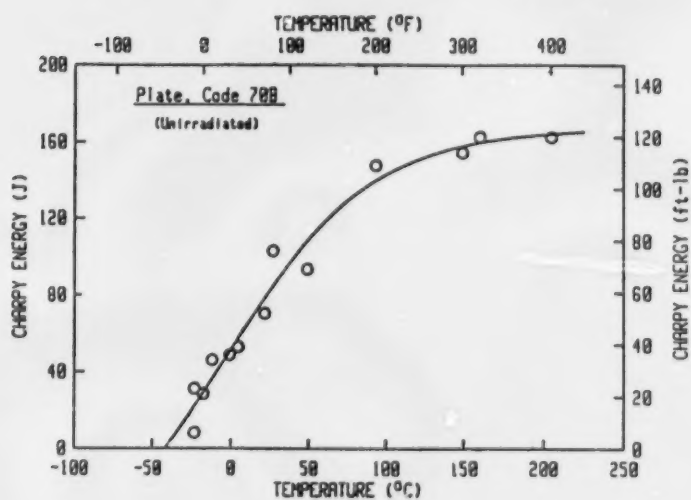


Fig. C-18 Charpy-V data for plate code 70B.

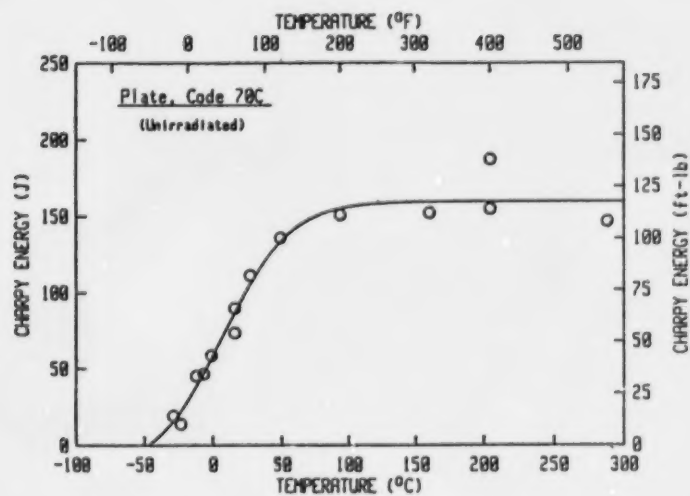


Fig. C-19 Charpy-V data for plate code 70C.

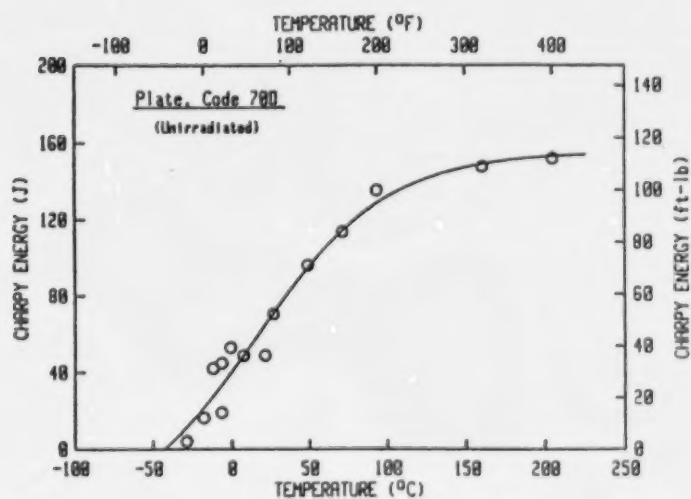


Fig. C-20 Charpy-V data for plate code 70D.

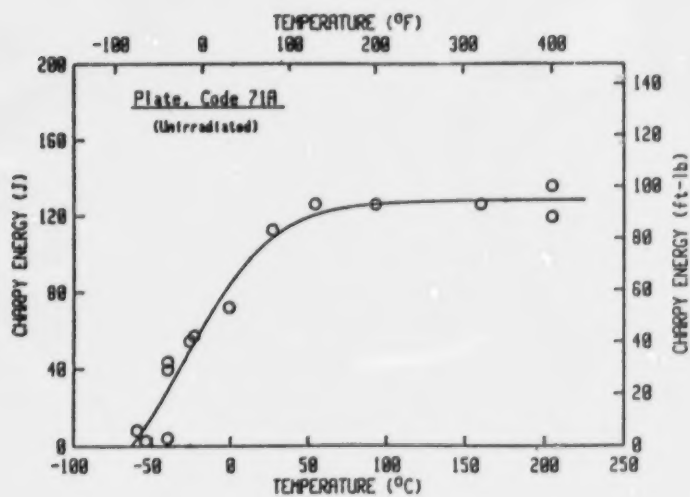


Fig. C-21 Charpy-V data for plate code 71A.

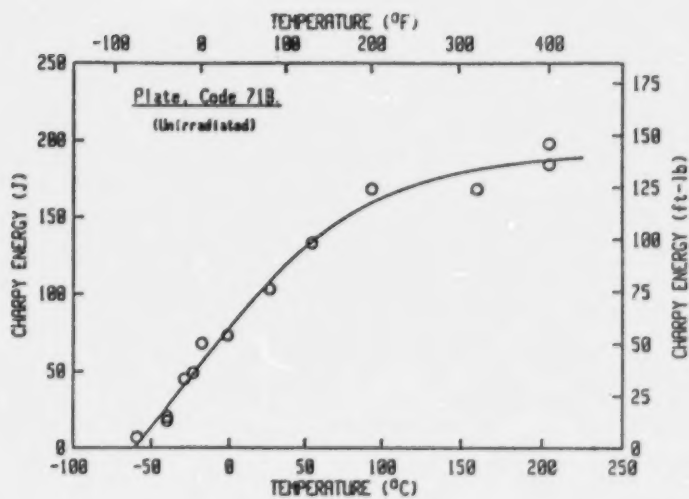


Fig. C-22 Charpy-V data for plate code 71B.

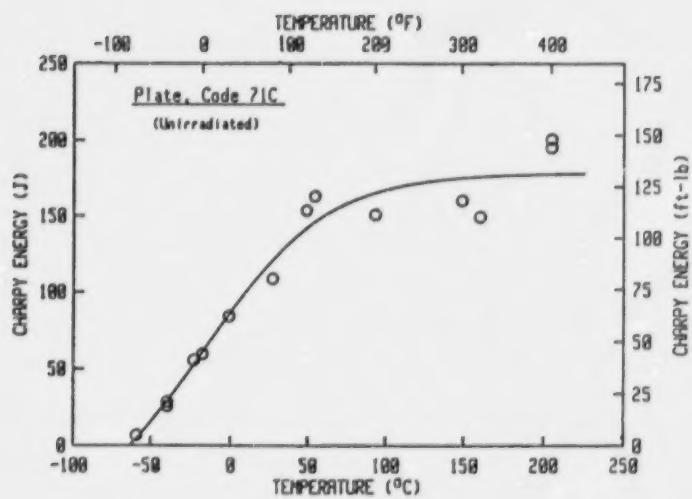


Fig. C-23 Charpy-V data for plate code 71C.

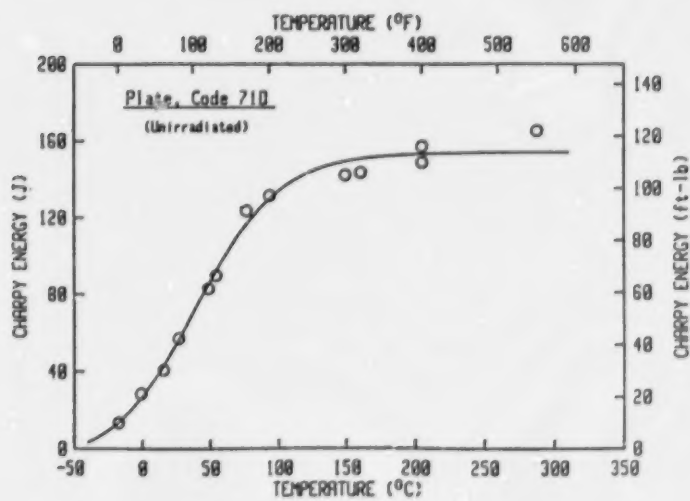


Fig. C-24 Charpy-V data for plate code 71D.

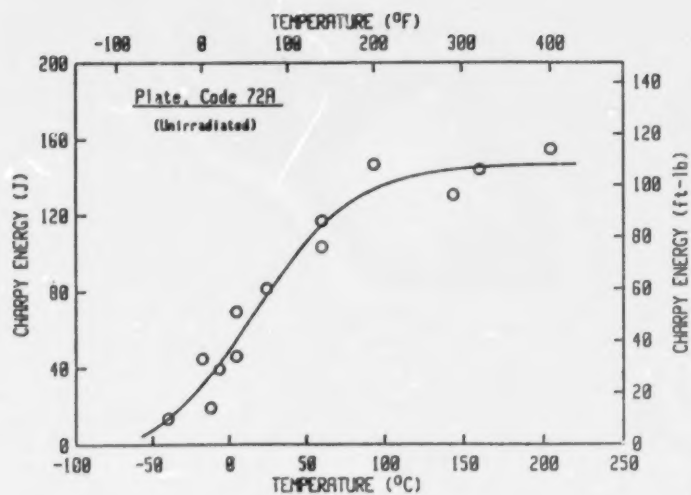


Fig. C-25 Charpy-V data for plate code 72A.

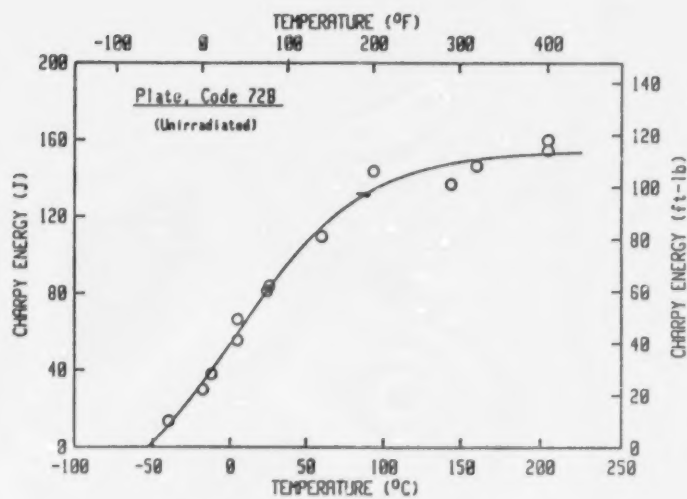


Fig. C-26 Charpy-V data for plate code 72B.

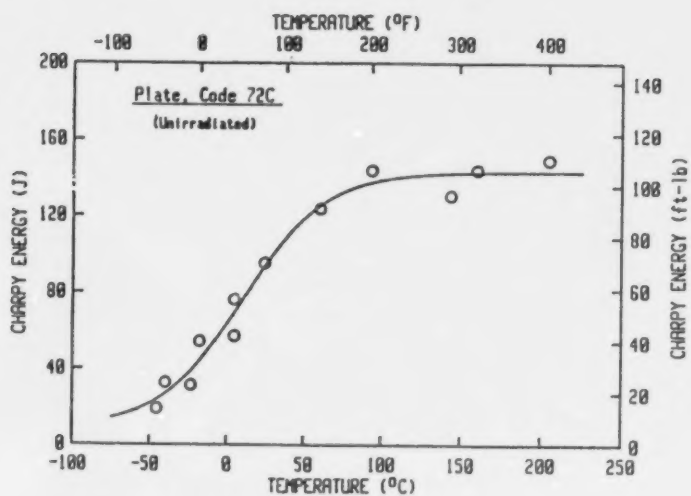


Fig. C-27 Charpy-V data for plate code 72C.

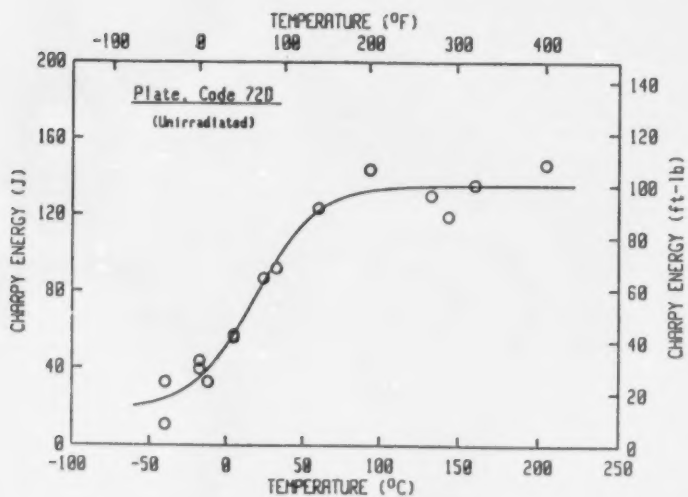


Fig. C-28 Charpy-V data for plate code 72D.

APPENDIX D

Tabulations of Irradiated-Condition Charpy-V Notch Ductility Test Data

Code 67A, UBR-39 (A & B Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
10	1	A	10 (50)	39 (29)	.51 (20)
12	1	A	32 (90)	76 (56)	1.09 (43)
32	3	A	93 (200)	146 (108)	1.70 (67)
6	1	A	4 (40)	52 (38)	.71 (28)
34	3	A	166 (330)	155 (114)	2.01 (79)
4	1	B	60 (140)	114 (84)	1.57 (62)
36	3	B	27 (80)	71 (52)	1.09 (43)
8	1	B	288 (550)	168 (124)	2.13 (84)
14	1	B	204 (400)	149 (110)	2.34 (92)
2	1	B	-7 (20)	20 (15)	.33 (13)

Code 67B, UBR-39 (A & B Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
14	1	A	166 (330)	133 (98)	1.57 (62)
32	3	A	4 (40)	7 (5)	.05 (2)
10	1	A	60 (140)	60 (44)	.84 (33)
36	3	A	93 (200)	92 (68)	1.30 (51)
4	1	A	32 (90)	45 (33)	.66 (26)
6	1	B	121 (250)	122 (90)	1.80 (71)
12	1	B	288 (550)	133 (98)	1.52 (60)
2	1	B	27 (80)	33 (24)	.53 (21)
34	3	B	160 (320)	119 (88)	1.88 (74)
8	1	B	204 (400)	130 (96)	1.78 (70)
38	3	B	43 (110)	38 (28)	.61 (24)

Code 67C, UBR-39 (A & B Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
36	3	A	160 (320)	114 (84)	1.65 (65)
8	1	A	-1 (30)	11 (8)	.15 (6)
12	1	A	93 (200)	73 (54)	1.12 (44)
14	1	A	121 (250)	125 (92)	1.57 (62)
4	1	A	60 (140)	49 (36)	.69 (27)
34	3	A	43 (110)	41 (30)	.64 (25)
6	1	B	288 (550)	117 (86)	1.80 (71)
2	1	B	204 (400)	119 (88)	1.68 (66)
38	3	B	88 (190)	64 (47)	**** (***)
10	1	B	27 (80)	35 (26)	.48 (19)

Code 67D, UBR-39 (A & B Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
32	3	A	288 (550)	106 (78)	1.78 (70)
8	1	A	110 (230)	83 (61)	1.19 (47)
34	3	A	74 (165)	49 (36)	.76 (30)
12	1	A	21 (70)	19 (14)	.23 (9)
6	1	A	93 (200)	66 (49)	.97 (38)
4	1	A	121 (250)	108 (80)	1.63 (64)
10	1	A	160 (320)	121 (89)	1.80 (71)
14	1	A	60 (140)	56 (41)	1.02 (40)
38	3	A	204 (400)	117 (86)	1.93 (76)
36	3	A	38 (100)	30 (22)	.43 (17)
2	1	B	54 (130)	35 (26)	.56 (22)

Code 68A, UBR-39 (B & C Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
10	1	B	138 (280)	50 (37)	.64 (25)
4	1	B	238 (460)	85 (63)	1.37 (54)
8	1	B	121 (250)	33 (24)	.48 (19)
14	1	C	177 (350)	89 (66)	1.32 (52)
2	1	C	93 (200)	22 (16)	.30 (12)
32	3	C	116 (240)	45 (33)	.61 (24)
36	3	C	204 (400)	92 (68)	1.30 (51)
34	3	C	160 (320)	60 (44)	.91 (36)
38	3	C	288 (550)	84 (62)	1.12 (44)
6	1	C	71 (160)	8 (6)	.05 (2)

Code 68A, UBR-39 (Annealed 850-168)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
12	1	B	38 (100)	114 (84)	1.63 (64)

Code 68B, UBR-39 (B & C Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
10	1	B	238 (460)	84 (62)	1.14 (45)
2	1	B	135 (275)	31 (23)	.41 (16)
34	3	B	138 (280)	26 (19)	.30 (12)
38	3	C	182 (360)	75 (55)	1.12 (44)
6	1	C	143 (290)	46 (34)	.58 (23)
8	1	C	116 (240)	28 (21)	.33 (13)
4	1	C	288 (550)	85 (63)	1.22 (48)
36	3	C	204 (400)	85 (63)	1.22 (48)
14	1	C	160 (320)	54 (40)	.79 (31)
32	3	C	71 (160)	7 (5)	0.00 (0)

Code 68C, UBR-39 (B & C Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
2	1	B	182 (360)	72 (53)	.99 (39)
12	1	B	238 (460)	73 (54)	1.14 (45)
10	1	C	116 (240)	26 (19)	.33 (13)
36	3	C	138 (280)	31 (23)	**** (***)
32	3	C	160 (320)	46 (34)	.64 (25)
4	1	C	204 (400)	80 (59)	**** (***)
8	1	C	82 (180)	8 (6)	0.00 (0)
6	1	C	288 (550)	76 (56)	1.45 (57)

Code 68C, UBR-39 (Annealed 850-168)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
38	3	B	38 (100)	68 (50)	.86 (34)
34	3	C	43 (110)	73 (54)	.91 (36)
14	1	C	193 (380)	150 (111)	1.83 (72)

Code 68D, UBR-39 (C Unit)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
8	1	C	238 (460)	76 (56)	1.04 (41)
12	1	C	182 (360)	53 (39)	.86 (34)
36	3	C	138 (280)	33 (24)	.41 (16)
6	1	C	116 (240)	24 (18)	.25 (10)
38	3	C	160 (320)	43 (32)	.53 (21)
34	3	C	204 (400)	80 (59)	.97 (38)
10	1	C	82 (180)	4 (3)	0.00 (0)
32	3	C	288 (550)	73 (54)	1.14 (45)

Code 68D, UBR-39 (Annealed 850-168)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
14	1	C	38 (100)	84 (62)	1.09 (43)
2	1	C	193 (380)	149 (110)	1.80 (71)
4	1	C	43 (110)	79 (58)	.99 (39)

Code 69A, UBR-40 (A & B Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
6	1	A	93 (200)	52 (38)	.81 (32)
10	1	A	138 (280)	136 (100)	1.88 (74)
37	3	A	49 (120)	35 (26)	.53 (21)
33	3	A	204 (400)	122 (90)	1.70 (67)
2	1	A	116 (240)	103 (76)	1.52 (60)
8	1	B	99 (210)	60 (44)	.94 (37)
35	3	B	77 (170)	38 (28)	.61 (24)
31	3	B	160 (320)	121 (89)	1.98 (78)
4	1	B	288 (550)	122 (90)	1.40 (55)
39	3	B	127 (260)	104 (77)	1.70 (67)

Code 69B, UBR-40 (A & B Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
2	1	A	93 (200)	45 (33)	.69 (27)
33	3	A	138 (280)	100 (74)	1.37 (54)
6	1	A	49 (120)	33 (24)	.48 (19)
37	3	A	204 (400)	123 (91)	1.70 (67)
10	1	A	116 (240)	92 (68)	1.40 (55)
35	3	B	127 (260)	73 (54)	1.17 (46)
41	3	B	77 (170)	19 (14)	.33 (13)
4	1	B	116 (240)	83 (61)	1.19 (47)
8	1	B	160 (320)	103 (76)	1.63 (64)
31	3	B	77 (170)	31 (23)	.46 (18)
39	3	B	188 (370)	107 (79)	1.57 (62)

Code 69C, UBR-40 (A & B Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
41	3	A	93 (200)	24 (18)	.38 (15)
37	3	A	77 (170)	35 (26)	.58 (23)
10	1	A	138 (280)	113 (83)	1.52 (60)
2	1	A	49 (120)	22 (16)	.36 (14)
33	3	A	204 (400)	121 (89)	1.65 (65)
6	1	A	110 (230)	73 (54)	1.12 (44)
31	3	B	121 (250)	72 (53)	1.09 (43)
4	1	B	99 (210)	60 (44)	.86 (34)
35	3	B	154 (310)	96 (71)	1.52 (60)
8	1	B	177 (350)	100 (74)	1.63 (64)
39	3	B	88 (190)	39 (29)	.64 (25)

Code 69D, UBR-40 (A & B Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
33	3	A	93 (200)	38 (28)	.53 (21)
39	3	A	288 (550)	94 (69)	1.50 (59)
6	1	A	135 (275)	83 (61)	1.40 (55)
2	1	A	138 (280)	103 (76)	1.50 (59)
4	1	A	49 (120)	16 (12)	.30 (12)
8	1	A	107 (225)	65 (48)	.97 (38)
31	3	A	204 (400)	114 (84)	1.32 (52)
37	3	A	104 (220)	54 (40)	.86 (34)
35	3	A	121 (250)	60 (44)	1.04 (41)
41	3	B	96 (205)	28 (21)	.43 (17)

Code 70A, UBR-54 (A & B Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
8	1	A	29 (85)	26 (19)	.43 (17)
31	3	A	93 (200)	88 (65)	1.30 (51)
35	3	A	38 (100)	43 (32)	.64 (25)
4	1	A	204 (400)	106 (78)	1.88 (74)
37	3	A	10 (50)	16 (12)	.30 (12)
6	1	A	66 (150)	53 (39)	.94 (37)
39	3	A	204 (400)	99 (73)	1.80 (71)
33	3	B	71 (160)	47 (35)	.81 (32)
2	1	B	43 (110)	38 (28)	.66 (26)
38	3	B	149 (300)	98 (72)	1.65 (65)

Code 70B, UBR-54 (A & B Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
8	1	A	32 (90)	19 (14)	.36 (14)
31	3	A	93 (200)	92 (68)	1.45 (57)
35	3	A	38 (100)	41 (30)	.69 (27)
4	1	A	204 (400)	123 (91)	2.06 (81)
37	3	A	10 (50)	15 (11)	.25 (10)
6	1	A	66 (150)	65 (48)	1.09 (43)
39	3	A	204 (400)	136 (100)	2.39 (94)
33	3	B	77 (170)	62 (46)	1.04 (41)
2	1	B	43 (110)	43 (32)	.74 (29)
10	1	B	60 (140)	65 (48)	1.12 (44)
38	3	B	149 (300)	117 (86)	1.75 (69)

Code 70C, UBR-54 (A & B Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
8	1	A	49 (120)	30 (22)	.48 (19)
31	3	A	93 (200)	56 (41)	.91 (36)
35	3	A	121 (250)	87 (64)	1.45 (57)
4	1	A	204 (400)	110 (81)	1.55 (61)
6	1	A	66 (150)	46 (34)	.76 (30)
39	3	A	204 (400)	114 (84)	1.60 (63)
33	3	B	104 (220)	62 (46)	1.04 (41)
2	1	B	77 (170)	46 (34)	.76 (30)
10	1	B	32 (90)	22 (16)	.33 (13)
38	3	B	160 (320)	102 (75)	1.63 (64)
37	3	B	132 (270)	100 (74)	1.63 (64)

Code 70D, UBR-54 (A & B Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
8	1	A	66 (150)	19 (14)	.25 (10)
31	3	A	93 (200)	35 (26)	.61 (24)
4	1	A	204 (400)	98 (72)	1.50 (59)
37	3	A	149 (300)	88 (65)	1.47 (58)
6	1	A	121 (250)	61 (45)	.99 (39)
39	3	A	216 (420)	104 (77)	1.60 (63)
33	3	B	82 (180)	15 (11)	.23 (9)
2	1	B	116 (240)	47 (35)	.89 (35)
10	1	B	138 (280)	73 (54)	1.14 (45)
35	3	B	110 (230)	45 (33)	.76 (30)

Code 71A, UBR-54 (A & B Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
37	3	B	60 (140)	61 (45)	1.07 (42)
8	1	B	27 (80)	37 (27)	.61 (24)
38	3	B	149 (300)	100 (74)	1.60 (63)
2	1	C	204 (400)	103 (76)	1.70 (67)
31	3	C	38 (100)	33 (24)	.48 (19)
35	3	C	66 (150)	62 (46)	1.09 (43)
6	1	C	93 (200)	89 (66)	1.45 (57)
39	3	C	204 (400)	100 (74)	1.75 (69)
33	3	C	21 (70)	22 (16)	.38 (15)
4	1	C	54 (130)	47 (35)	.81 (32)

Code 71B, UBR-54 (B & C Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
8	1	B	27 (80)	38 (28)	.56 (22)
37	3	B	182 (360)	114 (84)	2.01 (79)
2	1	C	49 (120)	58 (43)	.91 (36)
31	3	C	177 (350)	106 (78)	1.75 (69)
35	3	C	66 (150)	62 (46)	1.09 (43)
6	1	C	93 (200)	85 (63)	1.35 (53)
39	3	C	38 (100)	54 (40)	.84 (33)
41	3	C	204 (400)	126 (93)	1.70 (67)
33	3	C	121 (250)	108 (80)	1.70 (67)
4	1	C	10 (50)	30 (22)	.48 (19)
10	1	C	204 (400)	103 (76)	1.68 (66)
38	3	C	4 (40)	11 (8)	.15 (6)

Code 71C, UBR-54 (B & C Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
38	3	B	166 (330)	95 (70)	1.47 (58)
37	3	B	88 (190)	49 (36)	.86 (34)
8	1	B	160 (320)	107 (79)	1.50 (59)
31	3	C	38 (100)	30 (22)	.43 (17)
35	3	C	66 (150)	38 (28)	.58 (23)
6	1	C	93 (200)	62 (46)	.99 (39)
2	1	C	71 (160)	37 (27)	.66 (26)
39	3	C	204 (400)	106 (78)	1.68 (66)
33	3	C	121 (250)	76 (56)	1.30 (51)
4	1	C	21 (70)	9 (7)	.10 (4)
10	1	C	204 (400)	100 (74)	1.42 (56)

Code 71D, UBR-54 (B & C Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
37	3	B	182 (360)	91 (67)	1.32 (52)
8	1	B	82 (180)	26 (19)	.46 (18)
38	3	B	116 (240)	47 (35)	.84 (33)
2	1	C	138 (280)	73 (54)	1.19 (47)
31	3	C	121 (250)	58 (43)	.97 (38)
35	3	C	66 (150)	18 (13)	.30 (12)
6	1	C	93 (200)	31 (23)	.61 (24)
39	3	C	204 (400)	89 (66)	1.47 (58)
33	3	C	149 (300)	79 (58)	1.24 (49)
4	1	C	110 (230)	41 (30)	.64 (25)
10	1	C	204 (400)	85 (63)	1.45 (57)

Code 72A, UBR-40 (B & C Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
6	1	B	227 (440)	100 (74)	1.42 (56)
35	3	B	204 (400)	83 (61)	1.19 (47)
31	3	B	121 (250)	45 (33)	.64 (25)
2	1	B	104 (220)	35 (26)	.51 (20)
33	3	C	204 (400)	81 (60)	1.24 (49)
39	3	C	238 (460)	99 (73)	1.32 (52)
41	3	C	171 (340)	76 (56)	1.19 (47)
4	1	C	138 (280)	54 (40)	.81 (32)
8	1	C	288 (550)	87 (64)	1.37 (54)
37	3	C	93 (200)	19 (14)	.23 (9)

Code 72B, UBR-40 (B & C Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
6	1	B	227 (440)	84 (62)	1.24 (49)
31	3	B	121 (250)	24 (18)	.41 (16)
2	1	B	149 (300)	46 (34)	.79 (31)
37	3	C	204 (400)	73 (54)	1.09 (43)
10	1	C	238 (460)	84 (62)	1.14 (45)
39	3	C	138 (280)	43 (32)	.58 (23)
8	1	C	288 (550)	85 (63)	1.42 (56)
41	3	C	171 (340)	62 (46)	.89 (35)
33	3	C	93 (200)	8 (6)	.03 (1)

Code 72B, UBR-40 (Annealed 850-168)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
4	1	C	38 (100)	81 (60)	1.45 (57)

Code 72C, UBR-40 (B & C Units)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
2	1	B	102 (215)	22 (16)	.38 (15)
31	3	B	121 (250)	43 (32)	.61 (24)
6	1	B	149 (300)	65 (48)	1.02 (40)
37	3	C	204 (400)	85 (63)	1.24 (49)
10	1	C	116 (240)	45 (33)	.64 (25)
35	3	C	138 (280)	46 (34)	.69 (27)
4	1	C	288 (550)	81 (60)	1.27 (50)
41	3	C	93 (200)	18 (13)	.18 (7)
39	3	C	171 (340)	71 (52)	1.09 (43)
8	1	C	152 (305)	54 (40)	.81 (32)
33	3	C	238 (460)	87 (64)	1.07 (42)

Code 72D, UBR-40 (C Unit)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
8	1	C	238 (460)	85 (63)	1.19 (47)
10	1	C	149 (300)	50 (37)	.74 (29)
2	1	C	121 (250)	37 (27)	.46 (18)
39	3	C	138 (280)	41 (30)	.58 (23)
31	3	C	93 (200)	11 (8)	.10 (4)
41	3	C	116 (240)	26 (19)	.38 (15)
33	3	C	204 (400)	79 (58)	1.12 (44)
35	3	C	288 (550)	85 (63)	1.07 (42)

Code 72D, UBR-40 (Annealed 850-168)

Spec. No.	Plate Row	Exp. Unit	Test Temp C (F)	Energy J (ft-lb)	Lat. Exp. mm (mils)
37	3	C	38 (100)	42 (31)	.71 (28)
4	1	C	54 (130)	103 (76)	1.35 (53)
6	1	C	27 (80)	57 (42)	.89 (35)

APPENDIX E

Computer Curve Fitting of Irradiated-Condition Charpy-V Notch Ductility Test Data

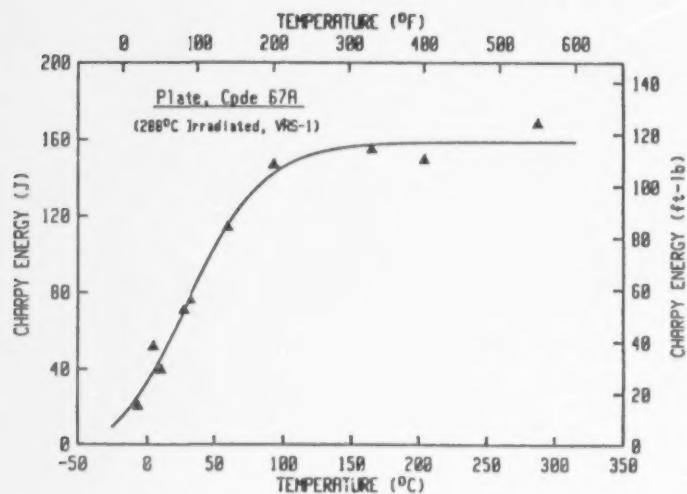


Fig. E-1 Charpy-V data for plate code 67A.

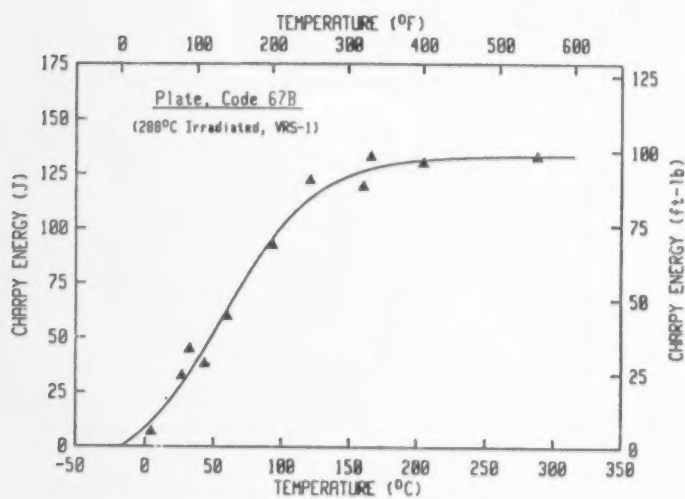


Fig. E-2 Charpy-V data for plate code 67B.

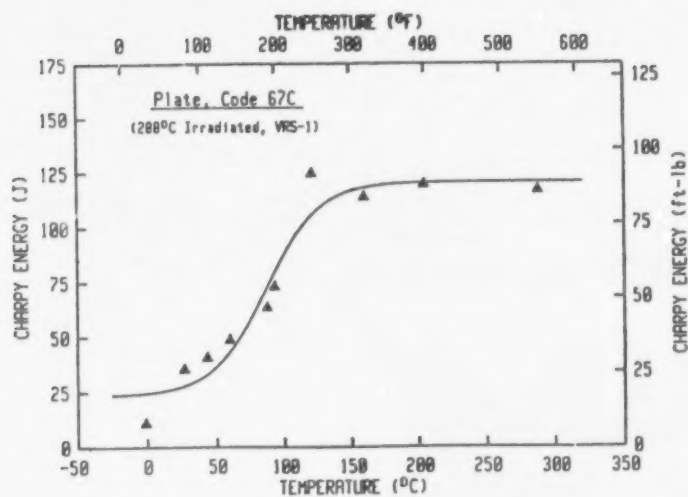


Fig. E-3 Charpy-V data for plate code 67C.

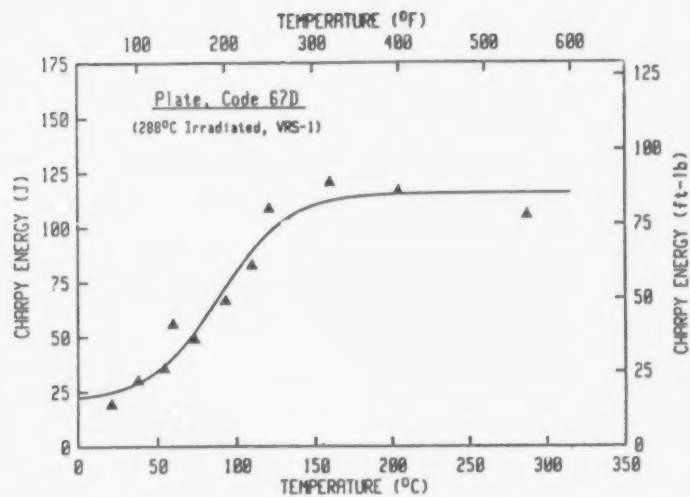


Fig. E-4 Charpy-V data for plate code 67D.

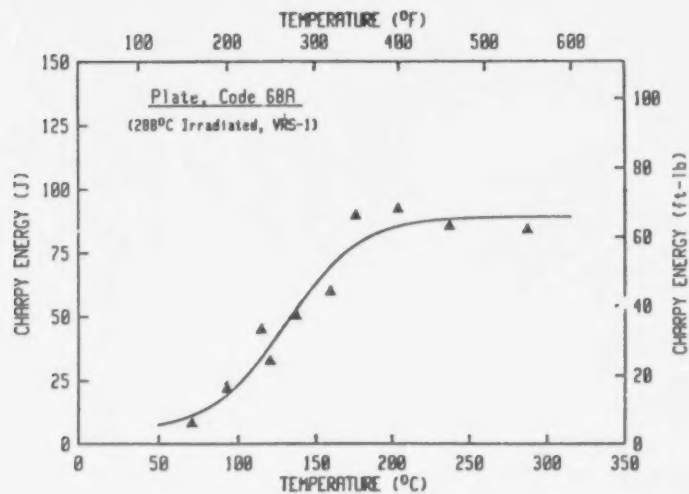


Fig. E-5 Charpy-V data for plate code 68A.

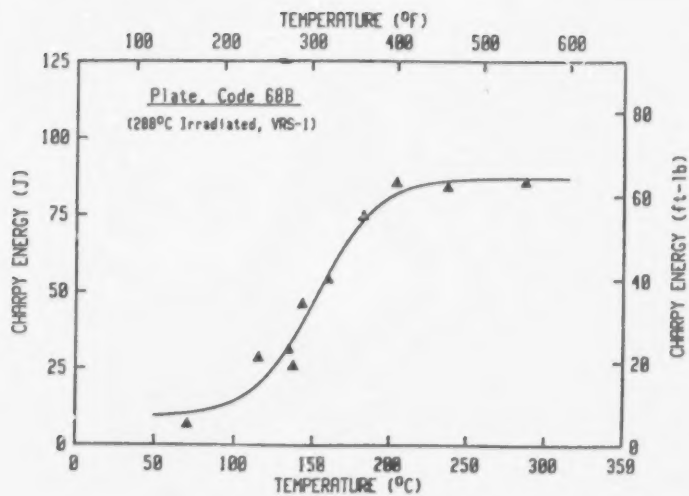


Fig. E-6 Charpy-V data for plate code 68B.

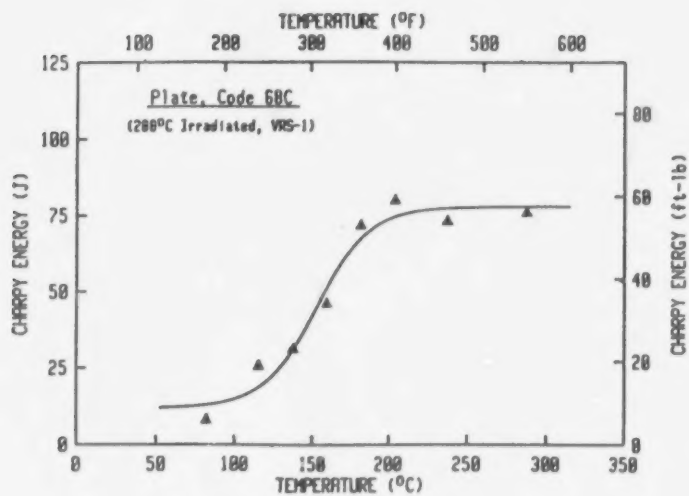


Fig. E-7 Charpy-V data for plate code 68C.

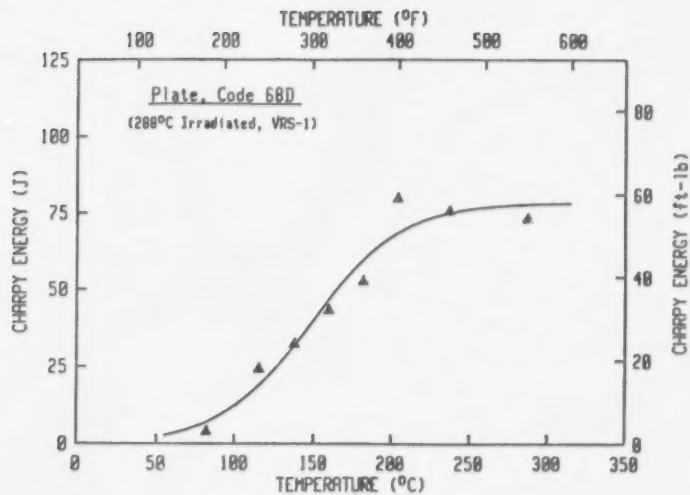


Fig. E-8 Charpy-V data for plate code 68D.

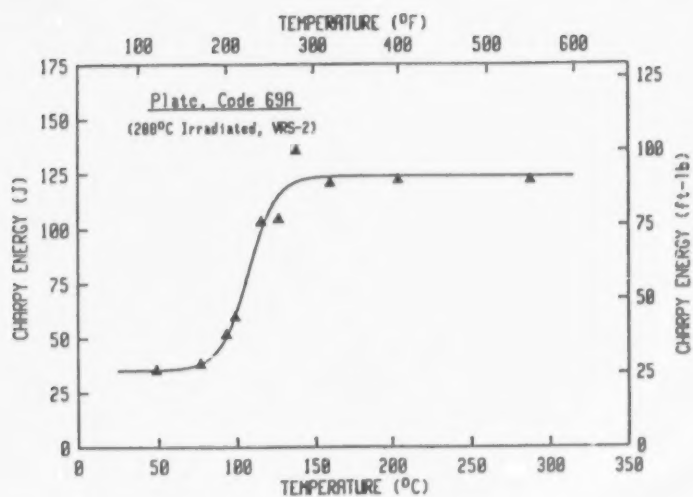


Fig. E-9 Charpy-V data for plate code 69A.

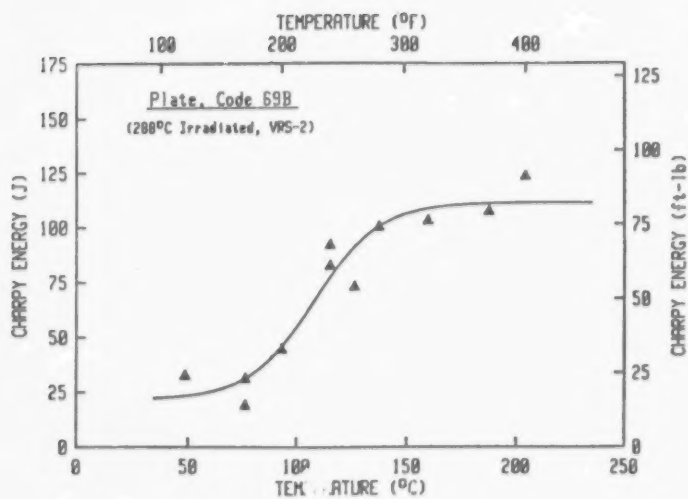


Fig. E-10 Charpy-V data for plate code 69B.

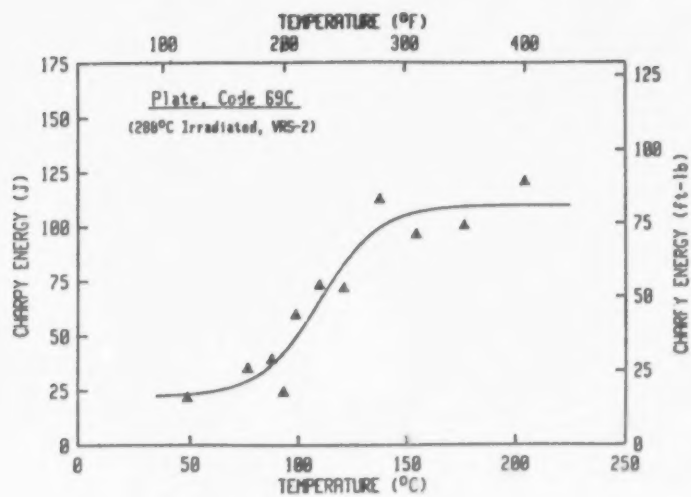


Fig. E-11 Charpy-V data for plate code 69C.

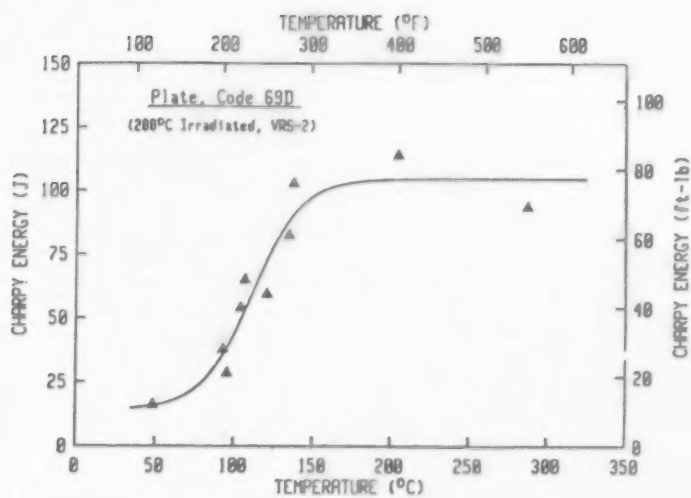


Fig. E-12 Charpy-V data for plate code 69D.

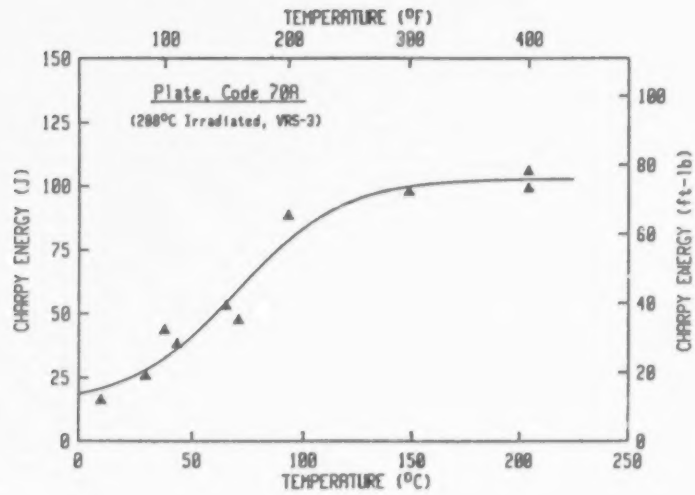


Fig. E-13 Charpy-V data for plate code 70A.

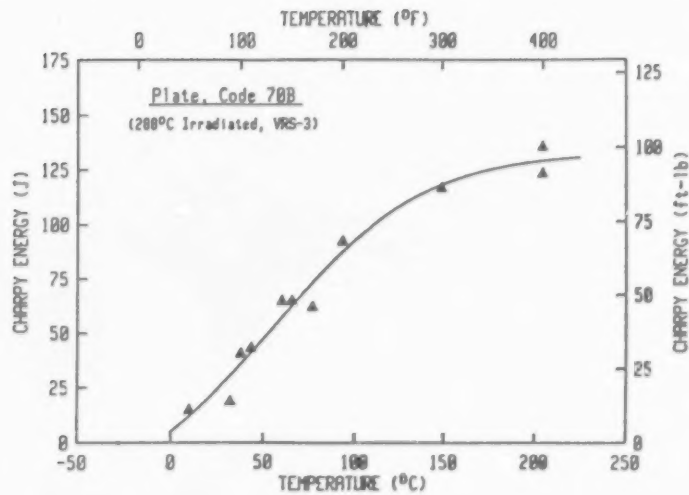


Fig. E-14 Charpy-V data for plate code 70B.

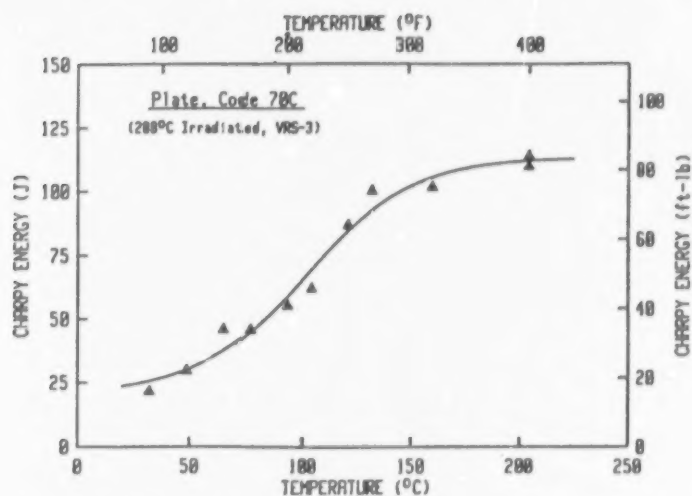


Fig. E-15 Charpy-V data for plate code 70C.

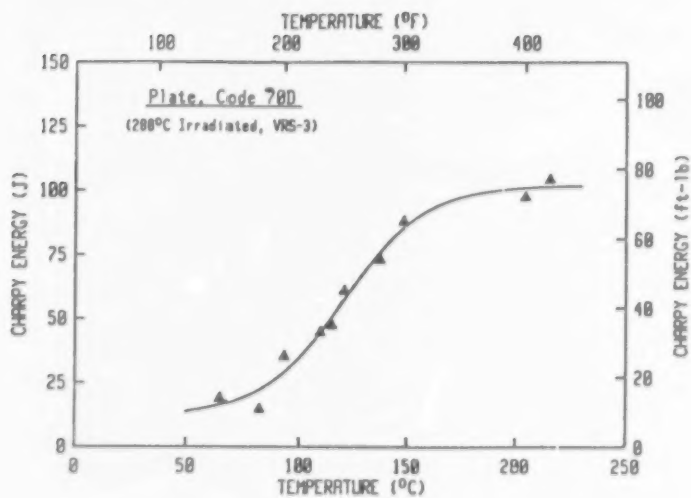


Fig. E-16 Charpy-V data for plate code 70D.

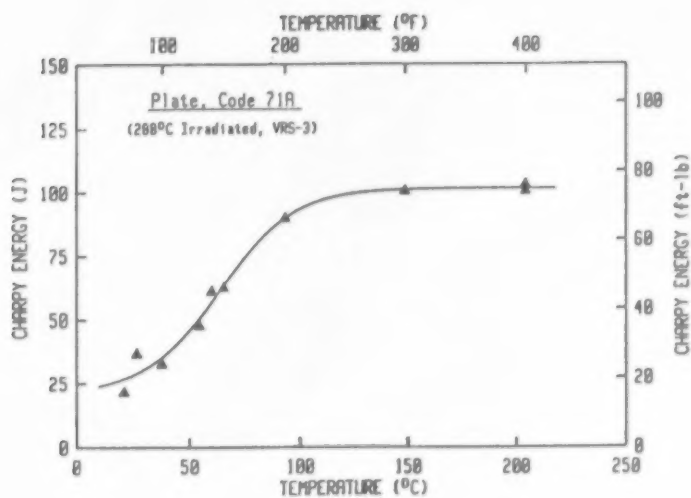


Fig. E-17 Charpy-V data for plate code 71A.

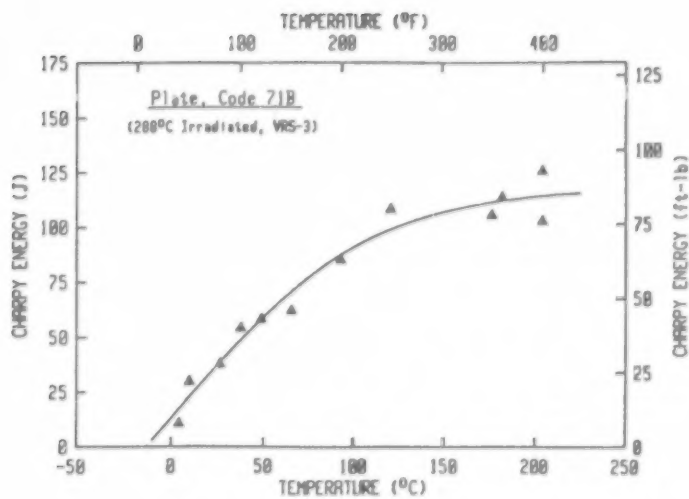


Fig. E-18 Charpy-V data for plate code 71B.

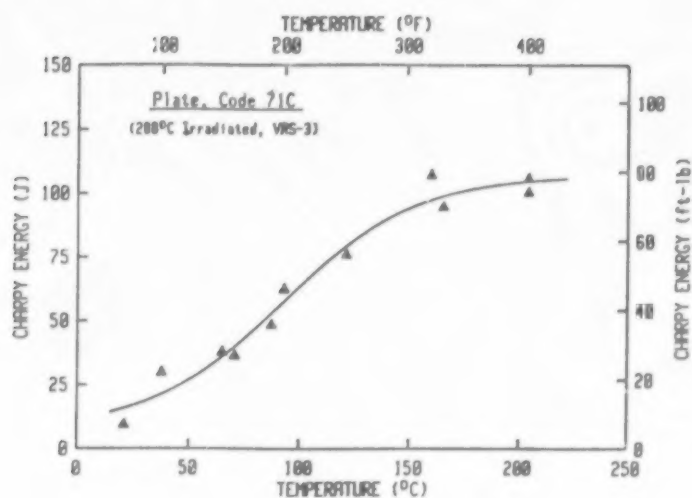


Fig. E-19 Charpy-V data for plate code 71C.

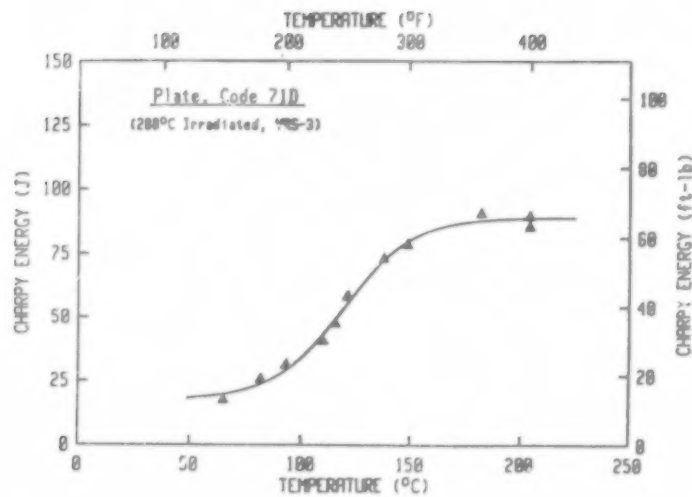


Fig. E-20 Charpy-V data for plate code 71D.

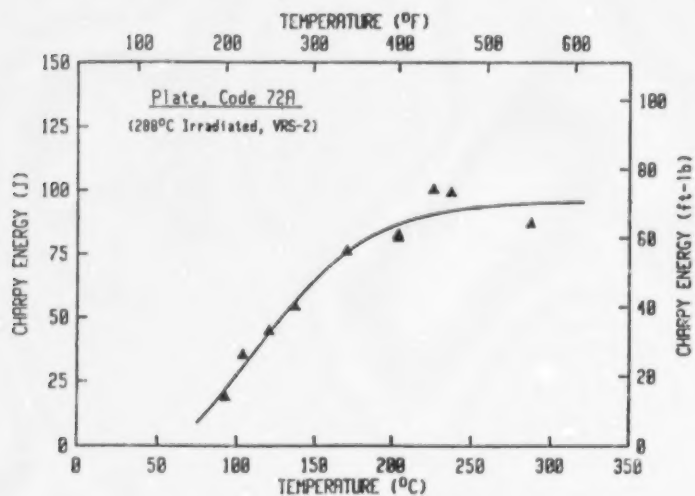


Fig. E-21 Charpy-V data for plate code 72A.

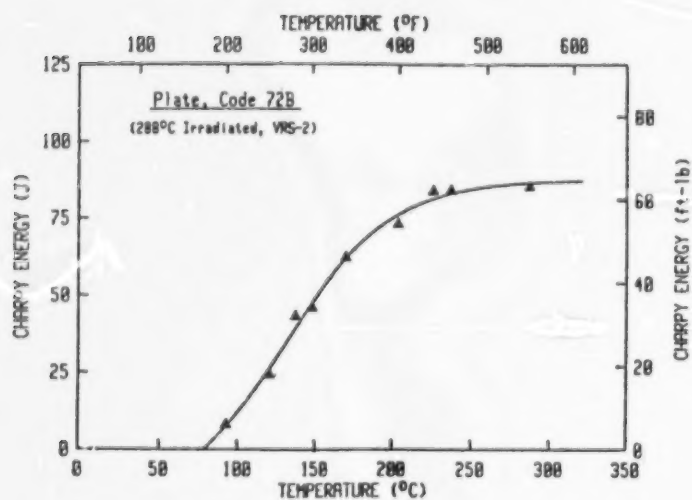


Fig. E-22 Charpy-V data for plate code 72B.

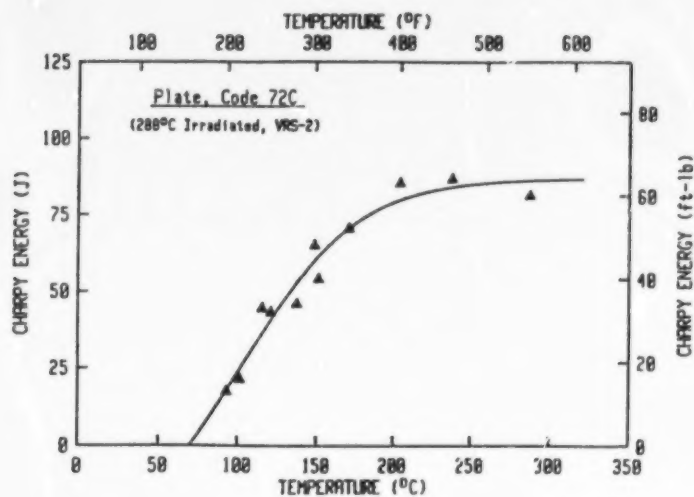


Fig. E-23 Charpy-V data for plate code 72C.

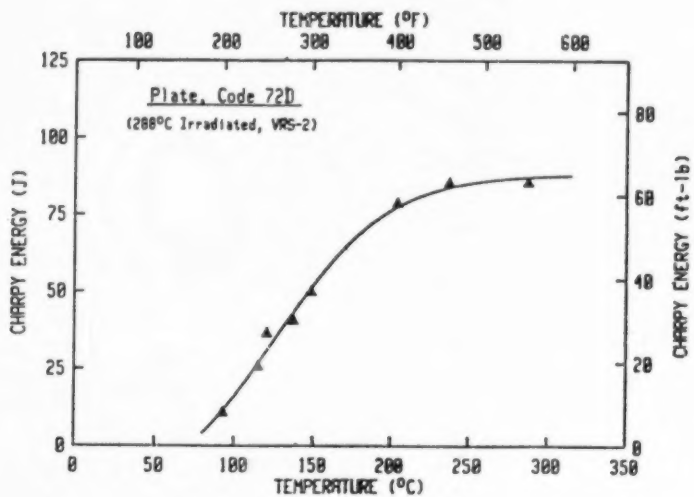


Fig. E-24 Charpy-V data for plate code 72D.

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16. ABSTRACT <i>(200 words or less)</i> This investigation with laboratory melts of pressure vessel steels (A 533-B or A 302-B base) probes suspect interactions between copper impurities and manganese, molybdenum, chromium and nickel alloying as influencing elevated temperature, radiation sensitivity development. The investigation also qualifies the influence of phosphorus content on radiation sensitivity as a function of copper content and explores suspect contributions of tin and arsenic. Radiation resistance is judged on the basis of Charpy-V (C_v) notch ductility before and after 288°C irradiation to $\sim 2.5 \times 10^{19}$ n/cm², $E > 1$ MeV. The findings demonstrate clearly that important composition interactions exist in radiation sensitivity development.					
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